Improved prediction of wheat yield response to nitrogen curves

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Abstract

Curves defining the yield response to nitrogen fertiliser can be used to decide on the optimal allocation of fertiliser between management units (paddocks, zones), if such curves can be reliably predicted by summary models. Simulated response curves in the southeastern Australian Mallee have been difficult to characterise because the range of potential shapes is not well fitted by a single function. A method that interpolates between 'key points' on the curve has only been partially successful. Simulated response curves and their parameters were thoroughly analysed to recommend improved methods of curve prediction. Response curves were generated by spline interpolation between nitrogen treatments in APSIM wheat simulation experiments, on 12 soil types in four southeastern Australian Mallee locations in each of 58 years. Linear regression models of yield and its first and second derivatives with respect to nitrogen were fitted by key environmental and management variables (break date, soil water on April 1, April-October rainfall, September-October temperature anomaly, and soil described by EC1:5) and their first-order interactions. Yield was fitted best (65.7-80.3% sum of squares over the range 0-180 kg/ha nitrogen at sowing), with first (42.1-75.3%) and especially second (26.0-68.2%) derivatives fitting less well, and being more affected by interactions and artefacts of interpolation. Parameters of first and second derivatives such as minimum, maximum, peak and trough could be used in various combinations to estimate 'key points'. None of the second derivative parameters, however, fitted well enough to recommend modelling 'key points' and linear interpolation between them. Better response curve predictions are likely to come from summary models of yield or its first derivative at simulated nitrogen rates, with spline interpolation in software used to complete response curves.

Key Words

Variable rate fertiliser, summary function, decision support software, nitrogen use efficiency

Introduction

An economically optimal decision on the allocation of a certain amount of fertiliser can be made between different land management units (paddocks, zones) if yield response curves are known for each unit in each possible season. Fertiliser is simply allocated to the zone with the highest marginal response, until the response in that zone decreases and another zone has a better response. A summary modelling approach is used to predict the response curves in software, for example Mallee Sustainable Farming's zonal nitrogen management tool (www.malleefocus.com.au/tools, Jones 2008b). Linear regression (summary) models based on farmer-level input data are used to summarize the features of response curves produced by crop simulation modelling.

Simulated nitrogen response curves had a variety of shapes in an initial analysis in the southeastern Australian Mallee (Jones 2008a). Besides the usual decline in response rate (i.e. Mitscherlich), some curves had increasing response rates at low levels (i.e. sigmoid), and limited yield decreases above the optimum. No one function would fit all curves, and attempts to predict which curve would be required in a particular situation were unrewarding. A single, more complex curve function would have been impossible to fit because in many years only part of the complete curve was observed. The proposed solution was to model the response as linear sections between 'key points' on each curve, such as the initial and peak response rate, and the nitrogen required for the peak response. Although some 'key points' were well fitted by linear regression models of environment and soil variables, some were not, and the ability of the models to predict response rates was only modest. This paper aims to more thoroughly analyse the curves to recommend improved methods of approximation.

Methods

Simulations

Response curves were derived from a simulation experiment using APSIM, which has had some validation for the nitrogen response in similar environments (Yunusa et al. 2004) and is the basis for the Yield Prophet system widely used by farmers and consultants in the area. Soil parameterization was based on soil and crop measurements at Carwarp, Euston, Loxton and Pinnaroo Mallee Sustainable Farming focus paddocks (Whitbread et al. 2008). Ten soil cores at each site were analysed for EC1:5, boron, chloride, crop lower and upper limit. Soils at each site were grouped into 'low', 'moderate' and 'severe' constraint zones, with representative soil cores used to make one 'average' soil for each zone (4 paddocks x 3 zones = 12 soils in total). The simulation treatments comprised the combination of all 12 soils, weather for the four locations (years 1950-2007) and nitrogen fertiliser applied as urea at sowing at rates 0, 7.5, 15, 30, 60, 90, 120 and 180 kg N/ha. Simulated crops were grown with a starting soil nitrogen of 40 kg N/ha (0-110cm). Soil water was reset each year on December 12 to a harvest lower limit determined by prior simulation. Surface residue was reset to 1.5 t/ha at the same time. Soil nitrogen and organic matter were reset on April 1 each year. Crops were sown soon after the break, according to a sowing rule based on rainfall and timing.

Analysis

Simulated yields were used to develop a nitrogen response curve for each soil – site – year combination. Curves were interpolated between nitrogen treatments (R statistical package smooth.spline and predict) and used to estimate first and second derivative of yield with respect to nitrogen (N) between N=1 and 179 kg N/ha. Yield and derivatives for each soil-site-year were also described by the maximum and minimum, the peak (where maximum > at N=1), and trough (where minimum < at N=1).

Key environment variables used in multiple linear regression (Genstat) were formed into groups, to accommodate non-linear responses and also anticipating uncertainty in input data provided by farmers: date of the break – 8 groups of 10 days after April 19th, soil available water on April 1 – 7 groups of 15mm from 0-15mm, and April-October rainfall – 6 groups of 50mm from 50-100mm. Spring temperature anomaly (Sep/Oct, compared to the 1961-1990 average, calculated as the average of daily max. and min.) and soil measurements were retained as continuous variables. Crop lower limit, soil chloride and EC1:5 (0-110cm) were all equally able to describe soil in regressions, but EC1:5 was chosen because of its close relationship to EM38 surveys in the area (Llewellyn et al. 2008). Regressions were limited to first order interactions to make analysis tractable, and also included location as a factor to fit variations in rainfall quantity/frequency.

Results

Response curve shape

Yield response to nitrogen curves (first derivative of yield with respect to fertiliser nitrogen; dY/dN) were visually inspected for all 2736 soil-site-year combinations. Of these, there was no yield (insufficient rainfall) in 35, and effectively flat (<2 kg yield/kg N min-to-max) yield response in 521 (19.0%). The remainder could be generalised into three basic types, the latter two simply segments of the first (Figure 1a). The first type ('a', 32.2% of curves) had an approximately linear rise in dY/dN to a peak, from which dY/dN fell approximately linearly to zero as more nitrogen was applied. A variation of this was for a small negative response at high nitrogen rates. In some curves the initial segment was flat or nearly so, and in some there was a small flat region before dY/dN began to rise. The second type ('b', 45.7% of curves) was the decline section of the first. The third, far less common type ('c', 1.8% of curves), began negative and rose to zero. The range of curves observed could not be reconstructed using simple response curves

(Figure 1d), but could be approximated by linear interpolation between key points if a few key parameters were known, for example initial and peak dY/dN, and minimum and maximum slope of dY/dN (the second derivative). If it were possible to predict the second derivative at N=1 (whether dY/dN initially increased or decreased), it would be possible to predict whether a model of type ‘a’ was required.

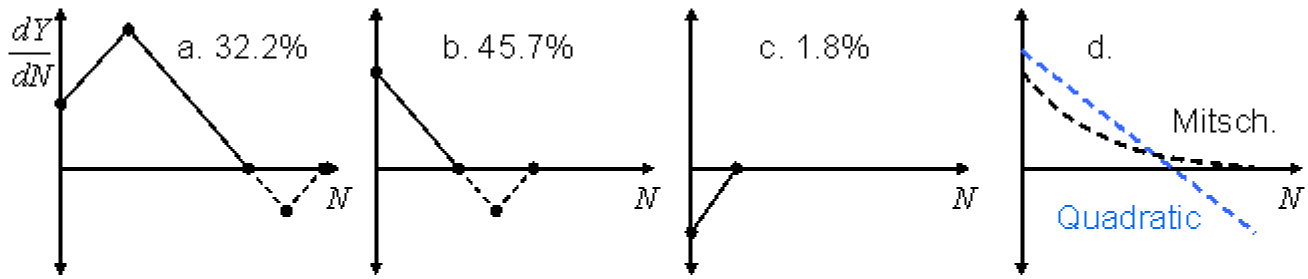

Figure 1a-d. Generalised shapes (a-c) for the first derivative of yield (dY/dN) with respect to fertiliser nitrogen (N). Dashed lines below the x-axis indicate variations where there is a small negative yield response to high rates of N. Mitscherlich and quadratic derivatives included for reference (d).

Curve analysis

The ability of summary models to predict yield and its derivatives was assessed by fitting linear regression models of environment and soil factors over the range of nitrogen rates. Variation in yield fitted better at high nitrogen rates. At low rates, more of the sum of squares related to first and higher order interactions, or was unexplained (Figure 2a). Variation in both first and second derivative showed some artefacts from the spline interpolation (curves were not smooth around the fertiliser rates = ‘knots’ in the spline; Figure 2b,c). Variation in first derivative (dY/dN) did not fit as well as yield, particularly at high nitrogen rates. Interactions were also more important for explaining variance in dY/dN at high nitrogen rates. Variation in the second derivative was poorly fitted especially at low nitrogen rates, without the use of higher order interactions or possibly a different analysis (e.g. non-linear).

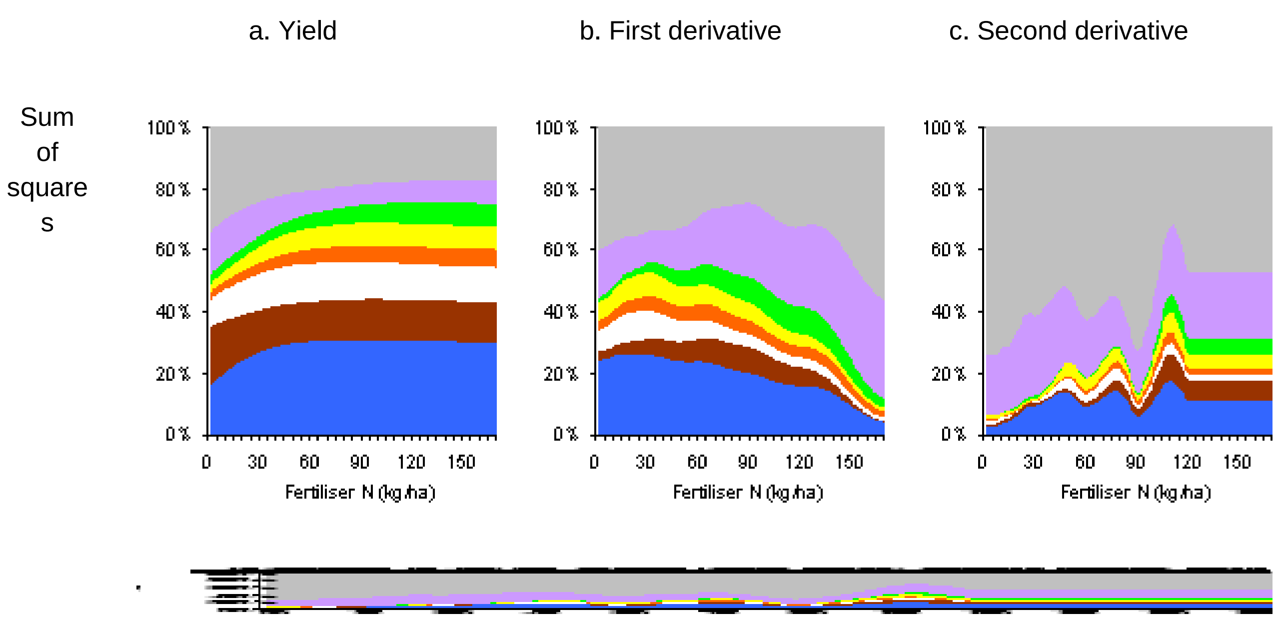

Figure 2. Sources of variation in sum of squares of a linear regression of yield (a), and its first (b) and second (c) derivatives with respect to fertiliser nitrogen, on soil and environmental variables

at fertiliser nitrogen rates between 1 and 179 kg N/ha. The 'interactions' are first order only; second and higher are included in 'residual'.

Ability to predict the maximum and minimum (all curves), and 'peak' and 'trough' (in curves where max. or min. wasn't at N=1), was also assessed to identify potential 'key points'. Maximum and peak yield and dY/dN fitted best of all curve parameters (Figure 3), with >60% of sum of squares fitted by main factors alone. Variation in minimum and trough dY/dN were fitted mainly by interactions. All second derivative parameters were quite poorly fitted (without including interactions), possibly because of spline artefacts.

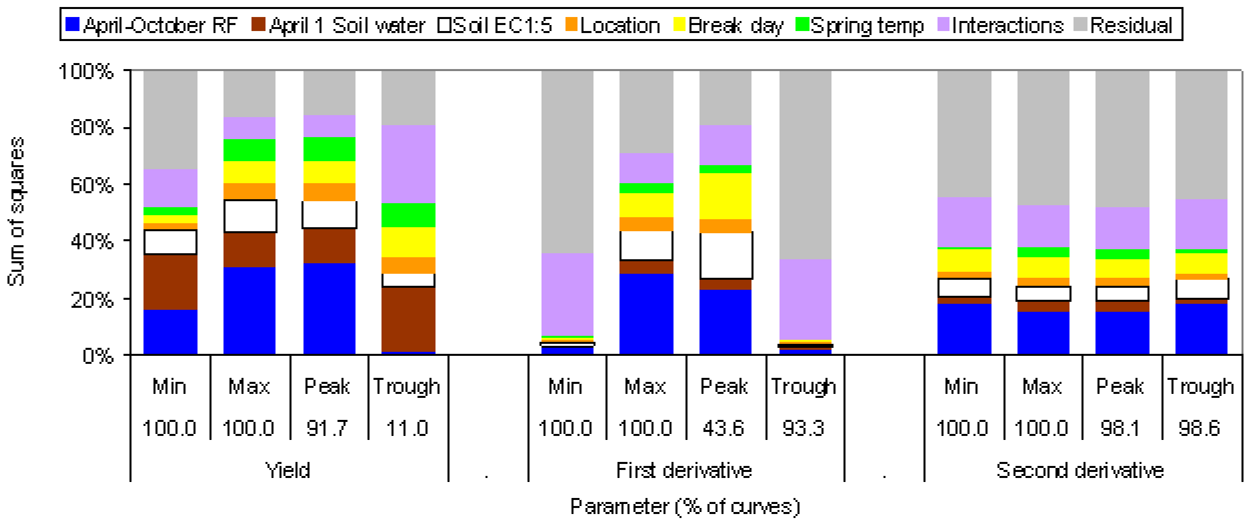

Figure 3. Sources of variation in sum of squares of linear regression of response curve parameters for yield and its first and second derivatives with respect to fertiliser nitrogen, on soil and environmental variables. 'Peak' and 'trough' were max. or min. measured on curves where max. or min. wasn't at N=1 (% shown).

Discussion

Curve shape

Many of the simulated response curves would be well fitted by Mitscherlich or quadratic curves, but a large proportion (32.2%) had an initial increase in response rate, which would require a sigmoid response curve (Figure 1). This may be related to the unusually low starting levels of mineral nitrogen in simulations, and/or a mechanism in APSIM such as increased root growth in response to nitrogen. Nitrogen also rarely decreased yield in simulations (only 1.3% > 100 kg/ha), at most by 400 kg/ha, whereas nitrogen-driven yield decreases of up to 900 kg/ha have been observed in field experiments in similar environments (van Herwaarden et al. 1998). This is an area for improvement in the APSIM model. Discrepancies between simulation and real crop behaviour are a limitation to the approach, but a crop simulation model is the only practical way to generate response curves.

Predicting curves

Yield fitted better than either derivative (Figure 2a-c). Assuming that better fits would also lead to better predictions, the best summary models might actually be obtained by modelling yield rather than dY/dN at the simulated nitrogen rates, and interpolating within the software to produce response curves. Summary models of dY/dN (also quite well fitted, Figure 2b) might also be quite effective, but likely to contain some errors from the initial spline interpolation. Both methods would have a similar number of parameters to the original 'key points' method. Modelling interpolated yield for every fertiliser rate is an alternative that would obviate the need for interpolation in the software, but lead to a large parameter set. All of these methods could reproduce any possible response curve shape.

Any summary model of ‘key points’, or a method that aims to predict which shape a curve will have, seems limited by inability to predict the initial (N=1 kg N/ha) and minimum and maximum of the second derivative (Figure 3). The initial would explain whether the curve had a peak in dY/dN, and the minimum and maximum would allow the position of the peak to be estimated (given that predictions of N required for peak dY/dN were poor in the original analysis). The difficulty of predicting the initial second derivative may relate to the complexity of the mechanisms causing the initial increase in response in some simulations and not others (see ‘Curve shape’ above). Uncertainty around the first ‘knot’ in the spline interpolation can be ruled out, because fits of the second derivative were poor over most of the nitrogen range (Figure 2c).

Linear regression on yield and dY/dN fitted well considering the grouping applied to environmental and management variables. Future work should test an assumption of linearity for soil water and rainfall (in which case grouping could be removed), and compare predicted with actual response rates.

Conclusion

Simulated yield response to nitrogen curves in Mallee paddocks were flat, had an initial increase phase and then a decline, or simply a decline. Yield was well fitted by a linear model of soil and environmental factors and their first-order interactions at most nitrogen rates. The first and particularly second derivatives were less well fitted without the use of more complex models. Curves of yield response to nitrogen are likely to be better predicted using summary models of yield or yield response at set nitrogen rates and interpolating between rates, rather than using the method of linear interpolation between ‘key points’, or deriving mathematical functions to predict curve shape and parameters.

References

Jones BR (2008a). Agronomy for N management under precision agriculture in the Mallee. www.malleefocus.com.au/pubs/MSF_2008_16-19.pdf. Accessed June 30 2010.

Jones BR (2008b). Tackling the precision agriculture problem - the MSF Zonal N Management Tool. www.malleefocus.com.au/pubs/MSF_2008_20-22.pdf. Accessed June 30 2010.

Llewellyn R, Whitbread A, Jones BR and Davoren B (2008). The role for EM mapping in precision agriculture in the Mallee. In 'Global Issues, Paddock Action'. (Australian Society of Agronomy: Adelaide).

van Herwaarden AF, Farquhar GD, Angus JF, Richards RA and Howe GN (1998). 'Haying-off', the negative grain yield response of grain yield to nitrogen fertiliser I. Biomass, grain yield, and water use. Australian Journal of Agricultural Research 49, 1067-1081.

Whitbread A, Llewellyn R, Gobbett D and Davoren B (2008) EM38 and crop-soil simulation modelling can identify differences in potential crop performance on typical soil zones in the Mallee. In 'Global Issues, Paddock Action'. (Australian Society of Agronomy: Adelaide).

Yunusa IAM, Bellotti WD, Moore AD, Probert ME, Baldock JA and Miyan SM (2004) An exploratory evaluation of APSIM to simulate growth and yield processes for winter cereals in rotation systems in South Australia. Australian Journal of Experimental Agriculture 44, 787-800.