Forecasting nutrient responses in annual crops

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Introduction

There is a strong need for quantitative advice on fertiliser rates for annual crops. The main approach used in New Zealand has been to recommend fertiliser applications that raise soil test values to target levels at which maximum yield is achieved (e.g., Cornforth and Sinclair, 1984; Wood *et al.*, 1984). However, the soil test values for maximum yields can vary between locations, seasons and crops. Furthermore, this method gives no indication of the optimum rates of fertiliser to apply - achieving maximum yield is often of dubious economic and environmental value. Factors such as time of sowing and irrigation also can have a marked influence on the response of crops to added fertiliser (Cooke, 1982). Models that quantitatively link yield with nutrient supply are needed to forecast economically and environmentally optimum fertiliser rates.

Here, I outline PARJIB, a new model for nutrient responses in annual crops. A key feature of the model is that the response to nutrient supply is conditioned by the potential yield and factors such as planting density and water stress. Linking nutrient responsiveness to potential yield gives the model portability between environments and seasons. A full mathematical description of PARJIB is beyond the scope of this paper, which outlines the key concepts that distinguish the model from its predecessors.

Model Overview

PARJIB uses standard soil chemical analyses as indices of nutrient supply from the soil, and allows for interactions between the effects of different nutrients. A departure from most earlier models is the idea that the responsiveness of a crop to nutrient supply is very strongly influenced by the maximum yield that is attainable in the absence of mineral nutrient stresses (Y_{max}). Environmental or management factors that increase Y_{max} will increase the responsiveness to applied fertiliser (Cooke, 1982; Ritchie, 1983). Y_{max} is calculated from potential yield, adjusted for water stress and planting density. Potential yield itself is calculated from models that describe how crops respond to the weather assuming no nutrient stresses (e.g., Charles-Edwards, 1982; Wilson *et al.*, 1995).

PARJIB deals with both yield and nutrient supply as scaled variables, unlike earlier models (e.g., Greenwood *et al.*, 1971; Greenwood and Karpinets, 1997a,b). This approach confers considerable flexibility upon the model, and especially helps the user to interpret the influence of factors such as planting density and water stress.

The concepts of scaling yield and nutrient supply are illustrated with an example for maize response to the amount of N supplied to the crop (N_{supply}). As N_{supply} increases from very small values, the economic yield increases from zero to a maximum value (Y_{max}) and then declines (Fig. 1). The scaled yield (Y^*) is defined as $Y/Ymax$. In the experiment summarised in Figure 1 Y_{max} is about 18 t/ha. N_{supply} is calculated as a weighted sum of N fertiliser applied and the amount available in the soil (measured here by Keeny and Bremner's (1966) anaerobic incubation test). Two particular values of N_{supply} are used for scaling, a low value (N_{min}) where both Y and Y* equal zero, and an optimum value (N_{opt}) where $Y=Y_{max}$ and $Y^*=1$. The scaled N_{supply} (N^*) is calculated as $(N_{supply} - N_{min})/(N_{opt} - N_{min})$. The response of Y* to scaled nutrient supply is readily described using a scaled, second order polynomial equation - where the exponents can take non-integer values. Figure 2 shows the data and N response function from Figure 1 scaled for use in the model.

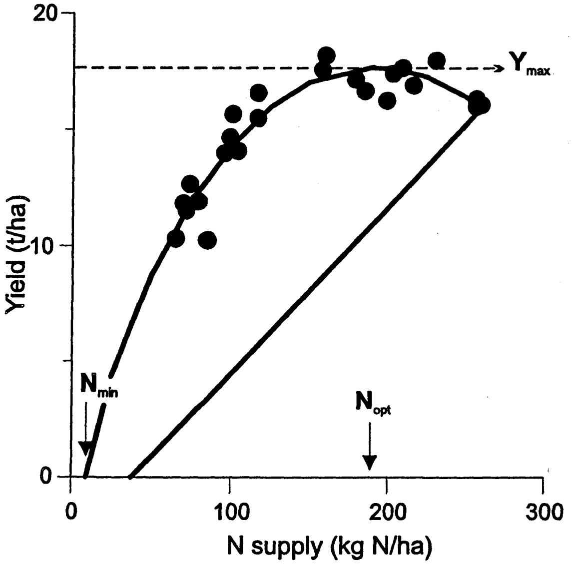
A benefit of this scaling is that Y* is readily adjusted for other stresses, such as the influence of water stress using the Penman or Active-ET model (French and Legg, 1979; Baird *et al.*, 1986).

Note that PARJIB does not attempt a nutrient balance for crops. Soil test values are used only as indices of soil supply, not as absolute measures of nutrients available for uptake. In our experience so far, using PARJIB does not require soil tests taken to the full rooting depth of the crop. Measurements from 0-15 cm depth have proven adequate, and including information for 15-30 cm does not significantly improve model performance.

PARJIB also allows for interactions between the effects of different nutrients. It does this by first predicting the reduction in Y* that is expected from each nutrient individually. Then a combined reduction in Y* is calculated from the square root of the sum of the squares of the reductions due to each nutrient. In practice this scheme predicts strong interactions between the effects of nutrients when two or more are in poor supply. Furthermore, if a nutrient is in short supply then applying more as fertiliser will raise yield by itself but it will also increase the response to further applications of other nutrients. This type of behaviour is common in practice (Cooke, 1982).

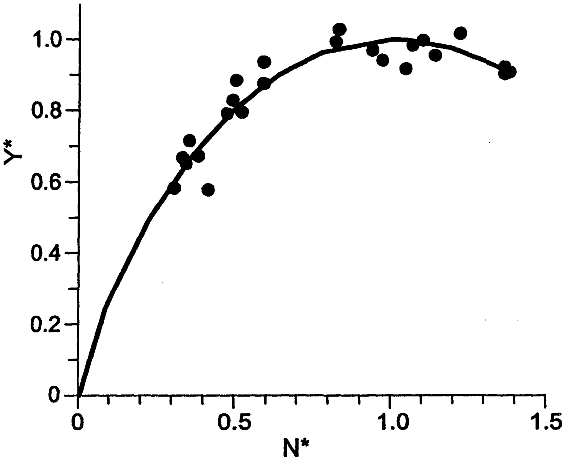
PARJIB requires calibration against field measurements of yield at different levels of nutrient supply. The best approach found so far is to supplement survey-style results with some experimental treatments where larger than usual amounts of fertiliser are applied. Factorial experiments, where for example N, P, and K supply are varied systematically, have proven expensive and offer little additional advantage. The main requirement is for a data set that encompasses a wide range of environmental conditions, including soil types, soil nutrient concentrations and fertiliser applications.

The calibration process usually involves estimating all of PARJIB's parameters simultaneously. For this a genetic algorithm was used (Holland, 1975; Goldberg, 1990).



This example shows the influence of N on grain yield of maize (unpublished data of McCormick and Reid). The crop was grown in 1995-96 in a Horotiu sandy loam near Cambridge. N_{supply} is a weighted sum of the fertiliser applied and the amount available in the soil (measured by anaerobic incubation at 40°C (Keeny and Bremner, 1966)). The depth of soil sampling was 0-15 cm only, separate soil tests were made for each plot. Fertiliser N was applied as urea and incorporated.

Figure 1. Illustration of the key parameters required for scaling yield and nutrient supply.



The data are from Figure 1. The fitted curve is a scaled, second-order polynomial with non-integer powers.

Figure 2. Response of scaled yield (Y*) to scaled N supply (N*).

Performance

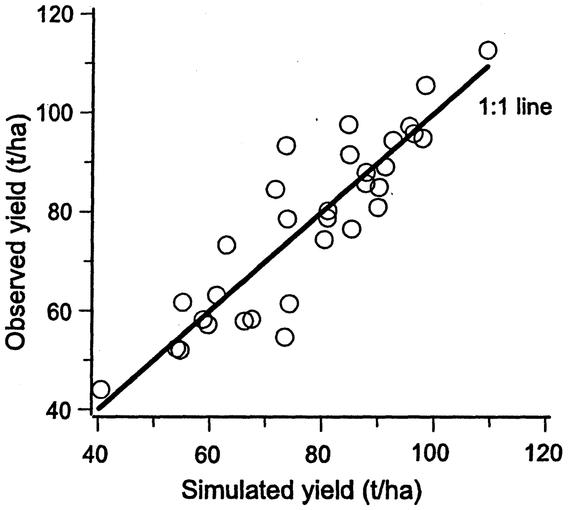
In the examples given below, all soil test results were from 0 to15 cm depth only.

For process tomatoes, the model was calibrated using data for two cultivars (Peto and Morse) over three seasons. All crops were grown in Hawke's Bay in a range of soil types, mainly alluvial silt loams and clay loams. Potential yield was estimated by a new model (Reid, unpublished data) that used solar radiation and air temperature information plus some cultivar-specific variables derived from earlier experiments. Simulated and observed yields generally agreed very well (Fig. 3). The calibration root mean square error was 7.8 t/ha. Linear regression of observed on simulated yields indicated that the model accounted for 80% of the observed variation in yield; the slope was 0.99 ± 0.090 and the intercept was 0.9 ± 8.0 t/ha. Clearly the model performed well, especially given the wide range of crop performance in the calibration dataset.

For sweet corn, the model was calibrated using results from three experiments conducted in Hastings (examining interactions between planting density and N, P and K fertilisers), and one experiment at Lincoln (examining crop response to water deficit). Potential yield was calculated using an adaptation of the model described by Wilson *et al.* (1995). Again simulated and observed yields agreed well (Fig. 4). The calibration root mean square error was 1.8 t/ha. Linear regression of observed on simulated yields indicated that the model accounted for 86% of the observed variation in yield; the slope was 1.03 ± 0.060 and the intercept was -0.7 ± 1.8 t/ha.

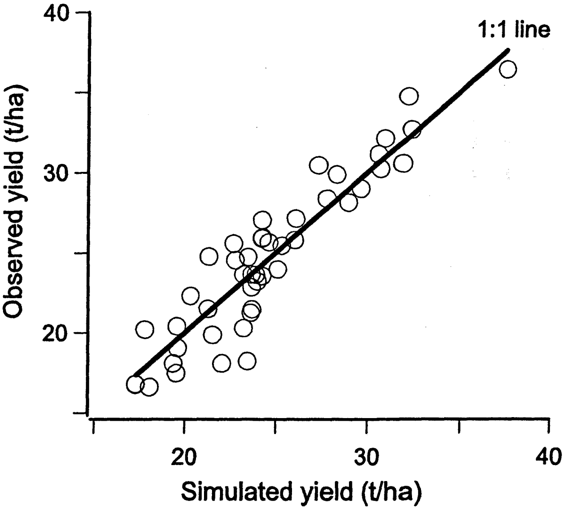
Discussion

PARJIB is a new model of how crop yield responds to nutrient supply. It is novel mainly in its use of potential yield, allowance for the effects of planting density and water stress, scaled variables for both yield



A wide range of fertiliser applications were included; usually N was applied as calcium ammonium nitrate or urea, P as superphosphate, and K as potassium sulphate.

Figure 3. Model performance for process tomatoes (*Lycopersicon esculentum* Mill) grown in commercial paddocks, Hawke's Bay 1995-1998.



A wide range of planting densities, soil water deficits, and fertiliser applications were included in the data set. Fertiliser N was applied as urea, P as superphosphate, and K as potassium sulphate.

Figure 4. Model performance for sweet corn (*Zea mays* L.) grown at Lincoln (1996-97) and in Hawke's Bay (1997-98).

and water supply, and method for dealing with interactions between nutrients. There is some precedent for our use of potential yield. Steele (1984) used what he called 'potential yield' as a basis for forecasting N fertiliser response. Steele calculated potential yield by multiplying the yield in the year against a 'relative yield' factor calculated from plant N concentration in the year before. Apart from requiring detailed information on previous crops in the same paddock, his method does not allow for differences in sowing date, weather, cultivar etc. Its applicability for crops other than maize and situations other than continuous monoculture is therefore rather less than that for PARJIB.

Results with vegetable crops so far indicate that PARJIB is successful in describing how yield varies across a fairly wide range of conditions. The model has strong promise as a means of predicting yield response to fertiliser applications, and particularly for identifying optimum rates of fertiliser. The following paper (Reid *et al.*, 1999) shows how the model can be used in this way for maize.

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