Does my potato crop need fertiliser? A modelling approach

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Abstract

A nutrient forecasting model (PARJIB) was calibrated using data from potatoes grown in Canterbury, Ohakune and Pukekohe over several years. The field experiments conducted in commercial paddocks were designed to build up data for response curves covering a wide range of nutrient supply rates. At harvest fresh and dry matter yields and the size distributions of tubers were measured. The model was calibrated using the pooled yield data from all experiments, using a genetic algorithm technique. After calibration the model explained 86% of the observed variation in yield. The model was then used to analyse crop performance in the Canterbury and Ohakune experiments. In Canterbury, yield losses due to nutrients were generally <8% and were mainly due to nitrogen limitation. In Ohakune, yield losses of up to 26% occurred due to nitrogen, phosphorous and potassium limitation. Addition of appropriate nutrients had significant effects on the size distribution of potatoes at Ohakune but not in the Canterbury experiments. The PARJIB model can be adapted to adjust yield and profitability forecasts to account for such shifts in tuber size distribution if the dollar value structure for the size categories is known. Maximising yields in the desired size range will require careful management of both fertiliser and the general agronomy of the crop.

Additional keywords: *Solanum tuberosum*, model, nutrient forecast, yield, size distribution, nitrogen, phosphorus, potassium

Introduction

Potatoes are grown under a wide range of conditions in New Zealand, both for processing and fresh market consumption. Early crops can have yields ranging from 15-50 t ha^{-1} and processing crops can have yields ranging from 40-80 t ha^{-1}. This range in yields is associated with an equally wide range of nutrient requirements to achieve those yields (Craighead and Martin, 2003). Importantly, nutrient supply can have significant consequences on product quality as well as yield (Allison *et al*., 2001; Rosen and Bierman, 2008). As a consequence, applying the correct amount of fertiliser is important to optimise yield and economic returns for growers.

While there are some quantitative methods for forecasting the best application rates of nitrogen (N) fertiliser (Jamieson *et al.*, 2006), there is little quantitative advice for the application of phosphorus (P) and potassium (K) for potato crops, or advice that takes account of interactions between the nutrients. It is therefore difficult for growers to know how much fertiliser is necessary to maximise yield and quality, as well as profit.

The requirement of a crop for nutrients depends on initial levels of soil fertility, water supply and conditions during growth (Wild, 1988). As a consequence optimum rates of fertiliser vary considerably between sites and seasons. As a result of this variation, a recipe approach does not result in economic or environmentally sustainable fertiliser applications. Therefore, to maximise profit and minimise environmental risks, growers need robust tools that help them to predict the amount of fertiliser required by the crop and at what rate.

One approach that has been used to optimise N, P and K fertiliser supply in a range of annual crops is the PARJIB nutrient forecasting model (Jamieson *et al*., 2001; Reid, 2002; Reid *et al*., 2002; Reid *et al*., 2004a; 2004b). PARJIB is a functionally-simple model and has the modest data requirements of response curve-style empirical models, but provides a meaningful framework for interpreting field experiments across a wide range of conditions (Jamieson *et al*., 2001; Reid *et al*., 2004b)

Here the PARJIB is calibrated for potato using data from a range of experiments and the calibrated model is used to interpret observations of current fertiliser practice in four experimental sites.

Materials and Methods

PARJIB Model

The cornerstone of PARJIB theory is that crop response to fertiliser depends upon the supply of nutrients from fertilisers *and* from the soil. In PARJIB both the nutrient supply and the simulated crop yield are expressed relative to the maximum yield (Y_{max}) that the crop could achieve without any nutrient limitations. This scaling is very important, because a crop with a low yield potential (due to say a small population density) will respond differently to a given nutrient supply than a crop with a high yield potential. Interactions between the effects of different nutrients are simulated using a simple equation that combines the effects of nutrients in less than optimal supply. Most importantly, the practical outcome of PARJIB is a series of fertiliser recommendations that account for initial soil nutrient supply and the target yield potential in a given field. This approach effectively transcends site and seasonal limitations often associated with traditional experimental approaches. Details of the model are described elsewhere (Reid, 1999; Reid, 2002; Reid *et al*., 2002).

PARJIB needs to be fitted or calibrated for different crop types, but usually it does not need separate calibrations for different soil types. Here, the model is calibrated for potatoes, using data from fertiliser-yield response experiments at seven different sites. The calibrated model is then used as an analytical tool to examine more deeply the causes of variation in crop performance at four of those sites. This approach has been used in a number of similar studies (Jamieson *et al*., 1984; Reid, 1990; Jamieson *et al*., 2001; Reid, 2002; Reid and English, 2000; Reid *et al*., 2002).

Experiments

The experiments were conducted either in Pukekohe, Ohakune or Canterbury (Table 1), covering a wider range of potato growing environments. Experiments 1-3 were originally designed to provide information on N or P and K responses across a range of potential yields and were used here as a source of data for model calibration. However these experiments give little information on interactions between crop responses to N, P and K. To remedy this situation extra experiments (experiments 4-7) were established to provide data on those interactions, while expanding the range of data available for model calibration. Experiments 4-7 were also used to provide cases studies for interpretation of current fertiliser practice.

Table 1: Production details of experiments 1 to 7.

	Experiment						
	1	2	3	4	5	6	7
Region	Canterbury	Pukekohe	Canterbury	Canterbury	Canterbury	Ohakune	Ohakune
Soil type	Templeton silt loam	Patumahoe clay loam	Templeton silt loam	Lyndhurst silt loam	Lyndhurst silt loam	Ohakune silt loam	Ohakune silt loam
Planting date	12 Oct 1998 2 Nov 1988 23 Nov 1988	2 May 2000	25 Oct 2001	31 Oct 2003	5 Nov 2003	15 Oct 2003	15 Oct 2003
Harvest date	27 Apr 2000	16 Oct 2001	10 Apr 2002	15 Apr 2004	21 Apr 2004	23 Mar 2004	23 Mar 2004
Planting density m^{-2}	2.4 4.8	6.2	4.8	3.5	3.6	2.9	2.9
Cultivar	Russet Burbank	Ilam Hardy	Russet Burbank	Russet Burbank	Russet Burbank	Franica	Franica

A summary of important production details for each experiment is provided in Table 1. Trial areas were prepared using conventional cultivation practices and apart from fertiliser treatments managed according to standard commercial practice.

Experiment 1 examined the interaction of planting density with sowing date and as such provides useful data on general crop growth. The experiment was planted at the Plant and Food Research farm at Lincoln, at three planting dates and two sowing densities replicated three times. Plot size was 4 rows wide and 5m long, with rows 0.86 m apart, the high sowing density having plant spacing’s of 30 cm between plants in a row, the low spacing density a spacing of 60 cm. Irrigation was applied at a rate of 40 mm when soil moisture deficit (SMD) reached 50 mm. Experiment 2 (Martin *et al.*, 2001) was a winter crop with four different rates of N fertiliser, replicated four times. Experiment 3 was planted to examine P and K responses of potatoes and was sown at the Plant and Food Research farm at Lincoln, on 25 October 2001. Plot size was 4 rows wide and 5 m long, with rows 0.86 m apart with spacing’s of 30 cm between plants in a row.

Experiments 4-5 were planted in commercial fields in Canterbury and experiments 6-7 were planted in commercial fields in Ohakune in 2003. Plots were 6 rows wide and 15 m long at each site. With the exception of fertiliser applications, soil and crop management followed standard commercial practices for each region.

Treatments

Fertiliser treatments used are summarised in Table 2. Specifically, experiment 1 had basal fertiliser of 120 kg Nha^{-1} and 100 kg ha^{-1} each of P and K as Nitrophoska® (12:10:10) applied by broadcasting at planting. A side-dressing of 50 kg N ha^{-1} as urea was applied approximately 50 days after planting for each sowing date. For Experiment 2, details of fertiliser treatment applications are described by Martin *et al*. (2001), but briefly rates were 0, 242, 350 and 472 kg N ha^{-1} applied at planting. Basal rates included 200 kg P ha^{-1}, 175 kg K ha^{-1} and 67 kg Mg ha^{-1}, applied as a blend of superphosphate, triple superphosphate, potassium chloride (KCl) and calcined magnesite (MgO). Experiment 3 had factorial combinations of 0, 25, 50, 100 and 150 kg P ha^{-1} applied as superphosphate and 0, 50, 100, 200, 250 kg K ha^{-1}applied as KCl. Fertiliser was broadcast over planted mounds and then covered with soil. The treatments of Experiment 4 and 5 concentrated upon responses to P (0, 171 or 341 kg P ha^{-1}) and K (0, 181, 361 kg K ha^{-1}) when there was ample N supplied (288 kg N ha^{-1}). Various combinations of N, P and K were used. N rates were designed to reflect typical values used in Canterbury.

The treatments of experiments 6 and 7 were combinations of rates of N (0 or 166 kg N ha^{-1}), P (0, 102, 321 kg P ha^{-1}) and K (0, 517 kg K ha^{-1}). The fertiliser rates were designed to span typical application rates used around Ohakune.

In experiments 4-7, most plots also received Mg at the rate the growers advised would normally applied; also included was a plot at each site with the full rate of N, P and K without Mg. Nitrogen fertiliser was applied as urea, P was applied as triple superphosphate, K as potassium sulphate and Mg as kieserite ($MgSO_4.H_2O$) in experiments 4 and 5 and a combination of kieserite and MgO in experiments 6 and 7. Fertiliser was broadcast over planted mounds and then covered with soil. For the grower treatment, fertiliser was applied at planting, with a third of N applied as a side-dressing.

Table 2: Fertiliser treatments used for experiments 1-7.

	Fertiliser rates kg ha^{-1}						
	Experiment 1	Experiment 2	Experiment 3	Experiment 4	Experiment 5	Experiment 6	Experiment 7
Basal fertiliser							
N	120						
P	100						
K	100						
Treatments							
N		0, 242, 350, 424		288, 388	288, 388	0, 166	1, 166
P			0, 25, 50, 100, 150	0, 170, 341	0, 170, 341	0, 102, 321	0, 102, 321
K			0, 50, 100, 200, 250	0, 180, 360	0, 180, 360	0, 517	0, 517
Mg				0, 22	0, 22	0, 135	0, 135
Growers fertiliser							
N				262	261	106	90
P				132	124	206	155
K				242	230	473	217
Mg				19	19	149	125

Measurements

In Experiment 1, a composite soil sample was collected from across the trial area. In all other experiments, samples were collected from each individual plot, immediately prior to planting. In all cases each soil sample consisted of a composite of 15-20 cores 0-15 cm deep and 2 cm diameter taken before planting and before fertiliser applications. Samples were thoroughly mixed, bagged and sent to commercial testing laboratories (Hill Laboratories) for chemical analysis. Basic soil data is summarised in Table 3. In addition, the concentrations of mineral N that could be extracted by 0.1 M KCl was measured prior to planting at depths of 1-15, 15-30, 30-45 and 45-60 cm. Again commercial laboratories conducted the analysis.

Potato yields were determined at commercial maturity. For this, 2 m sections from the two middle rows of each plot were marked and the number of tops counted to estimate plant population. Tubers were then hand-dug, graded into four standard size categories (<75mm, 75-150 mm, 150-250 mm, >250 mm along the stem to rose axis), counted and weighed fresh. A representative sub-sample of eight tubers from each size category was used to estimate dry matter (DM) content, determined after oven-drying to constant mass at 70°C. For experiments 4-7, 5 m sections of the two inner rows were harvested in a similar manner. Tubers were graded into 6 distinct size categories reflecting commercial grades (<25 mm, 25-50 mm, 50-75 mm, 100-125 mm and >125 mm across the widest point). Tuber length was recorded to assist direct comparison of grades with tubers from experiments 1-3. Length, diameter, specific gravity and dry matter % of at least 100 tubers from each experimental site were measured. Equations were developed from this data to convert the size distributions measured in all the experiments to standard size distributions based on the preferred commercial size grades

Table 3: Soil test results averaged for each experimental site.

	Experiment						
	1	2	3	4	5	6	**7**
N (kg N ha^{-1})[1]	64	19	61	76	57	131	114
Olsen P (ug ml^{-1})	26	155	17	19	21	24	7
Pretention	25	90	25	23	27	94	95
Exchangeable K (meq 100g $^{-1}$)	0.27	1.55	0.67	0.42	0.28	0.50	0.23
TBK (meq 100g $^{-1}$)[b]	2.51	0.50	2.74	2.51	2.28	0.26	0.07
Mg (meq 100g $^{-1}$)	0.58	1.16	0.54	0.22	0.37	1.02	0.62
CEC (meq 100g $^{-1}$)	13.0	17.8	13.0	11.2	11.4	17.0	14.3
AWC (mm)	180	180	180	85	85	330	330

[1]Readily mineralisable N, measured by anaerobic incubation at 40°C (Keeney and Bremner, 1966).
[2]Reserve potassium, measured by the tetraphenol boron test (Carey and Metherell, 2003).

Analysis

Wherever possible, yield data from each individual plot was used to calibrate the PARJIB model. However, this was not appropriate for Experiment 1, where the soil test results were obtained from the overall trial site. Hence for Experiment 1, only replicate means were used in the calibration process. This gave a grand total of 94 calibration data points.

PARJIB scales nutrient supply by relating it to Y_{max}, the maximum yield in dry matter that could be achieved at each site without nutrient limitation. This step is important as it enables direct comparisons of fertiliser responses for crops at different sites experiencing different weather. Usually Y_{max} is taken to be the potential yield at a standard plant population and within the model this is adjusted for water stress and plant population before being used to scale the supply of N, P and K. Here the process is simplified by using the Potato Calculator™ (Jamieson *et al.*, 2006). Y_{max} is estimated from the Potato Calculator™ prediction of yield after inputting the observed amounts and distribution of mineral N in the soil at each site at planting, and the actual amounts and timing of N fertilisers and irrigation.

During the calibration process it appeared that soil P retention (or Anion Storage Capacity) and reserve K exchange capacity (TBK) affected the supply of nutrient and response of the crop. Neither P retention nor TBK values were included in the original formulation of PARJIB. Here a simple adjustment is used to allow for a proportion of the reserve K to become available during growth and for the effectiveness of P fertiliser to be reduced in proportion to the P retention values.

The actual fitting was achieved using a genetic algorithm technique that identified the combination of parameter values that gave the smallest root mean square error (RMSE) when the simulated yield values were compared with those actually observed.

The calibrated model was then used to interpret the effects of the growers' current fertiliser practices (Table 2) on plant nutrition and yield at the sites for experiments 4-7. To do this, values of the scaled nutrient supply and yield were simulated for each plot using growers' normal fertiliser applications.

To evaluate the effect of nutrients on size distribution the actual experimental treatment rates were used. The percentage yield loss due to each nutrient was estimated and regressed against tuber size, to evaluate effect on percentage of small (less than 75 mm) or large tubers (greater than 75 mm).

Results

Model calibration

Observed fresh tuber yields across all sites ranged from 11.1-83.4 t ha^{-1} with an average of 50.9 t ha^{-1}. The model was fitted using DM yields, with observed values ranging from 2.05-17.9 t ha^{-1}, averaging 11.7 t ha^{-1}. Pooling results from all 7 experiments the model accounted for 86% of the observed variation in yield (Figure 1), with a mean error of 0.005 t ha^{-1} and an RMSE of 1.5 t ha^{-1}. A least squares regression of observed yield on simulated yield had a slope of 1.01 (standard error 0.043) and an intercept of -0.1 (standard error 1.6), indicating a good statistical fit.

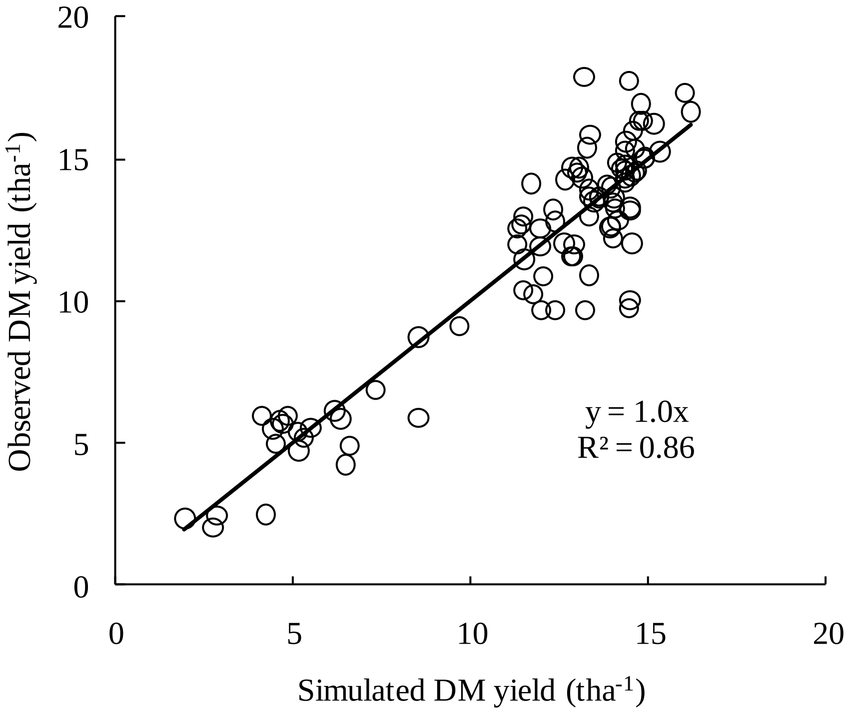

Figure 1: Comparison of yields simulated by PARJIB and observed yields for experiments 1-7. All yields are expressed as dry matter of the tubers. RMSE=1.5 t ha^{-1}, mean error = 0.005 t ha^{-1}.

Effects of fertilisers on yield and tuber size

The results of analysing grower fertiliser rates (Figure 2) indicate that N was usually less than optimally supplied - largely because the fitted value of the N fertiliser efficiency was only 11% of that for native soil N. Simple water balance calculations using Penman-Montieth estimates of evapotranspiration suggested that, during growth, drainage through the root zone at experiments 4, 5, 6 and 7 was 92, 79, 418 and 418 mm respectively. This could be expected to have leached a considerable fraction of the fertiliser N applied and so it is perhaps not surprising that the fitted value for the N fertiliser efficiency was small. Despite the apparently low values of the scaled N supply, the model predicted that yield losses due to inadequate N were always <9% (Figure 3). This reflects a diminishing returns style of yield response to fertilisers. When using the experimental rates of N supplied to each plot, the decrease in yield estimated by the simulated yield loss due to insufficient N, was associated with a rise in the proportion of small (<75 mm) tubers (Figure 4). Regression analysis showed that tuber number decreased with increasing simulated yield loss due to N supply (Table 4).

For experiments 4, 5 and 7, the model indicated that the scaled nutrient supply values for P were also inadequate under the grower's fertiliser regime (Figure 2). Clearly the model is suggesting that rather larger rates of P fertilisation could have increased yield, although as with N the simulated yield losses due to inadequate P were quite small (Figure 3). For the Canterbury sites (experiments 4 and 5) there was no discernable effect of decreasing P supply on tuber size distribution (Figure 5) or tuber number (Table 4), although at Ohakune (experiments 6 and 7) there was some indication that decreasing P supply increased the proportion of small tubers and significantly (P<0.001) decreased tuber number (Table 4).

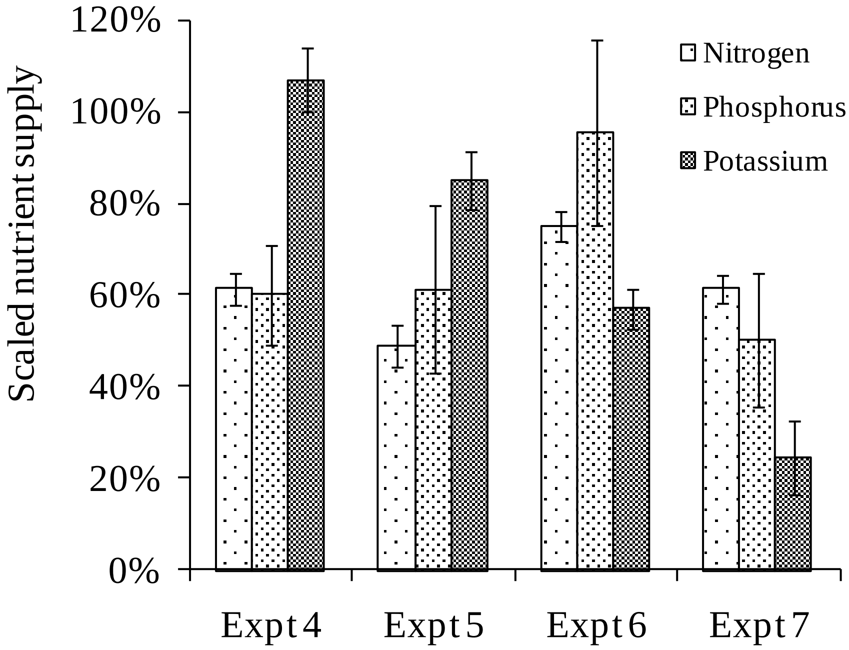

Figure 2: Simulated values of the scaled nutrient supply index for crops receiving the growers' normal fertiliser applications at experiments 4-7. Bars are standard errors of means.

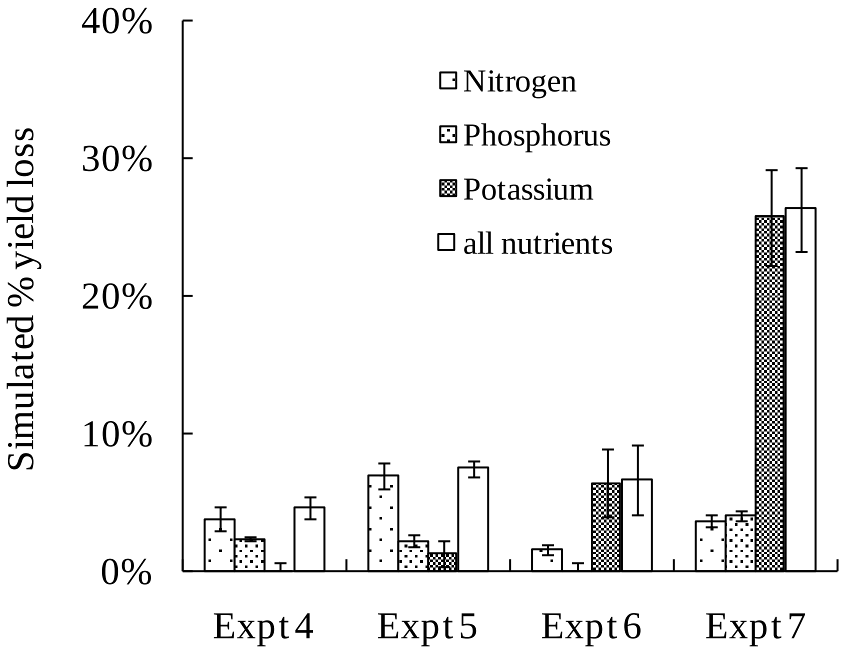

Figure 3: Simulated percentage yield loss with grower fertiliser rates at the different experiment sites. Experiments 4 and 5 were conducted in Canterbury, experiments 6 and 7 were conducted at Ohakune. Bars are standard errors of means. Note that the total simulated yield loss is less than the sum of the yield losses due to individual nutrients (see equation 11 of Reid, 2002).

Table 4: Regression analysis statistics of relationships between yield loss due to N, P and K supply and tuber number per m^2 for each plot of experiments in Canterbury and Ohakune.

	Canterbury			Ohakune		
	N	P	K	N	P	K
P value	0.019	0.335	0.065	0.047	0.001	0.004
R^2	0.26	0	0.15	0.12	0.49	0.27
Intercept	35.5	32.8	33.0	49.3	49.3	51.7
± standard error	1.3	39.8	0.7	2.7	1.6	2.6
slope	-0.69	-0.12	-0.92	-1.57	-0.37	-0.50
± standard error	0.27	0.12	0.46	0.75	0.08	0.16

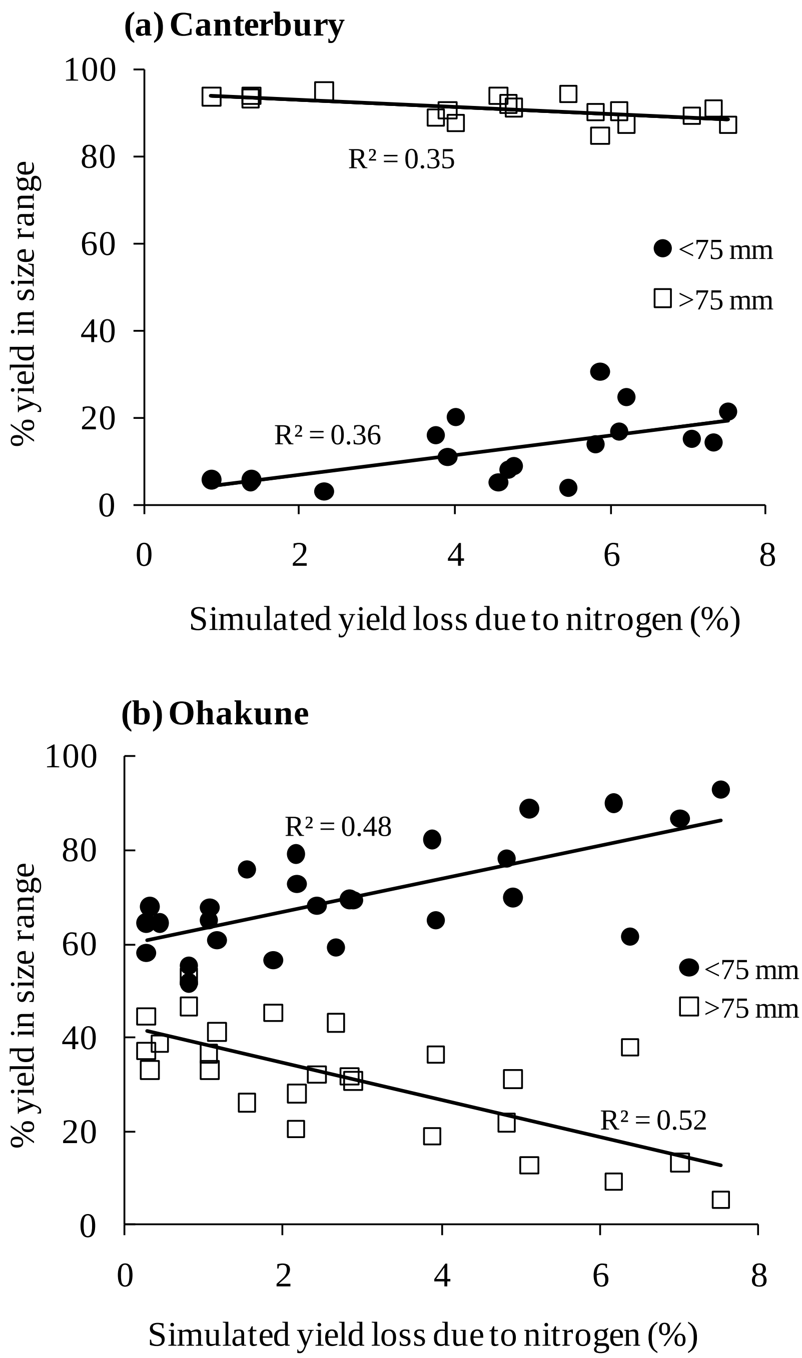

Figure 4: Relationship between simulated yield loss due to N and percentage of yield in tubers of size grades <75 mm and >75 mm for (a) experiments 4 and 5 in Canterbury and (b) experiments 6 and 7 in Ohakune.

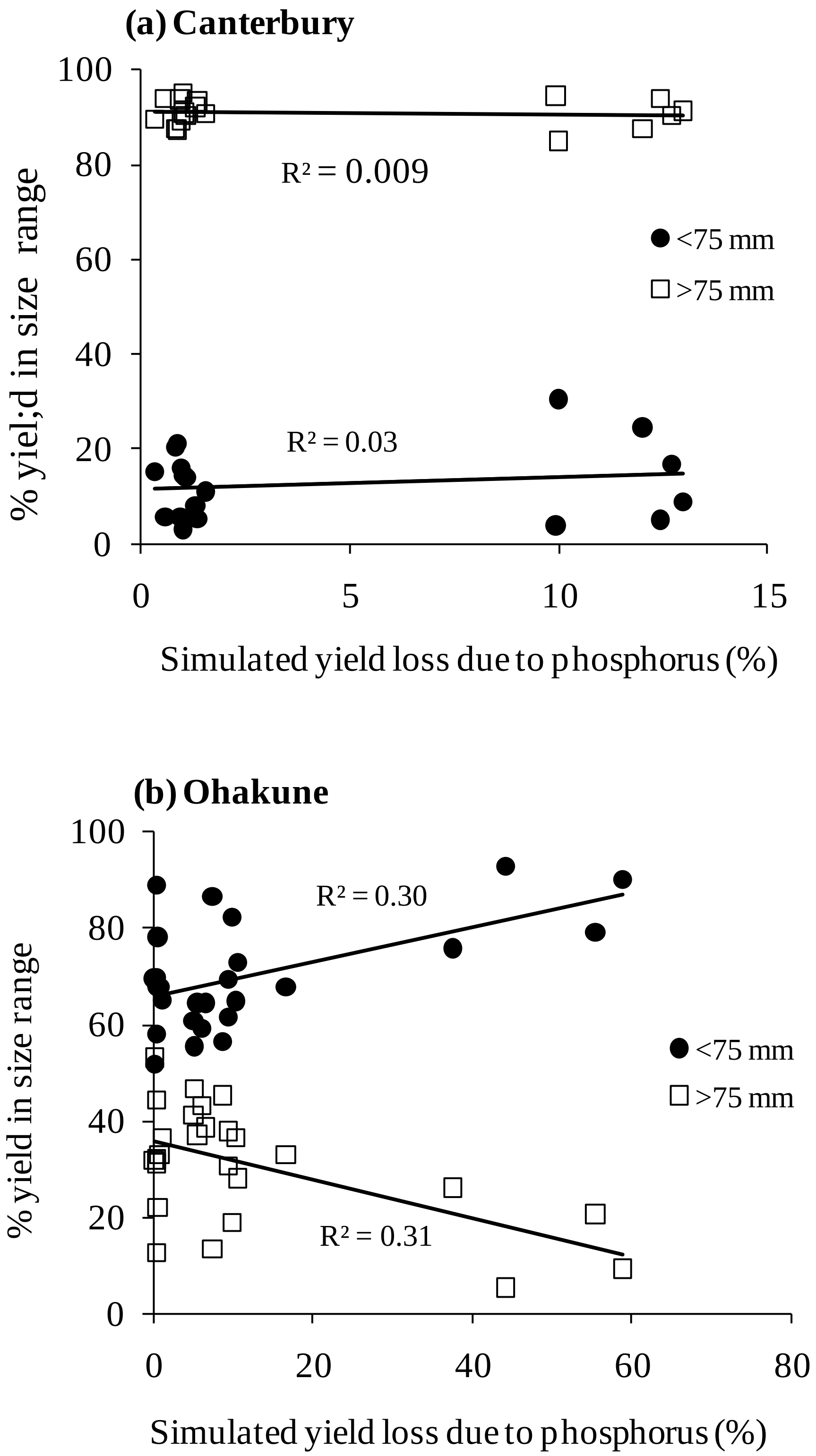

Figure 5: Relationship between simulated yield loss due to P and percentage of yield in tubers of size grades <75 mm and >75 mm for (a) experiments 4 and 5 in Canterbury and (b) experiments 6 and 7 in Ohakune.

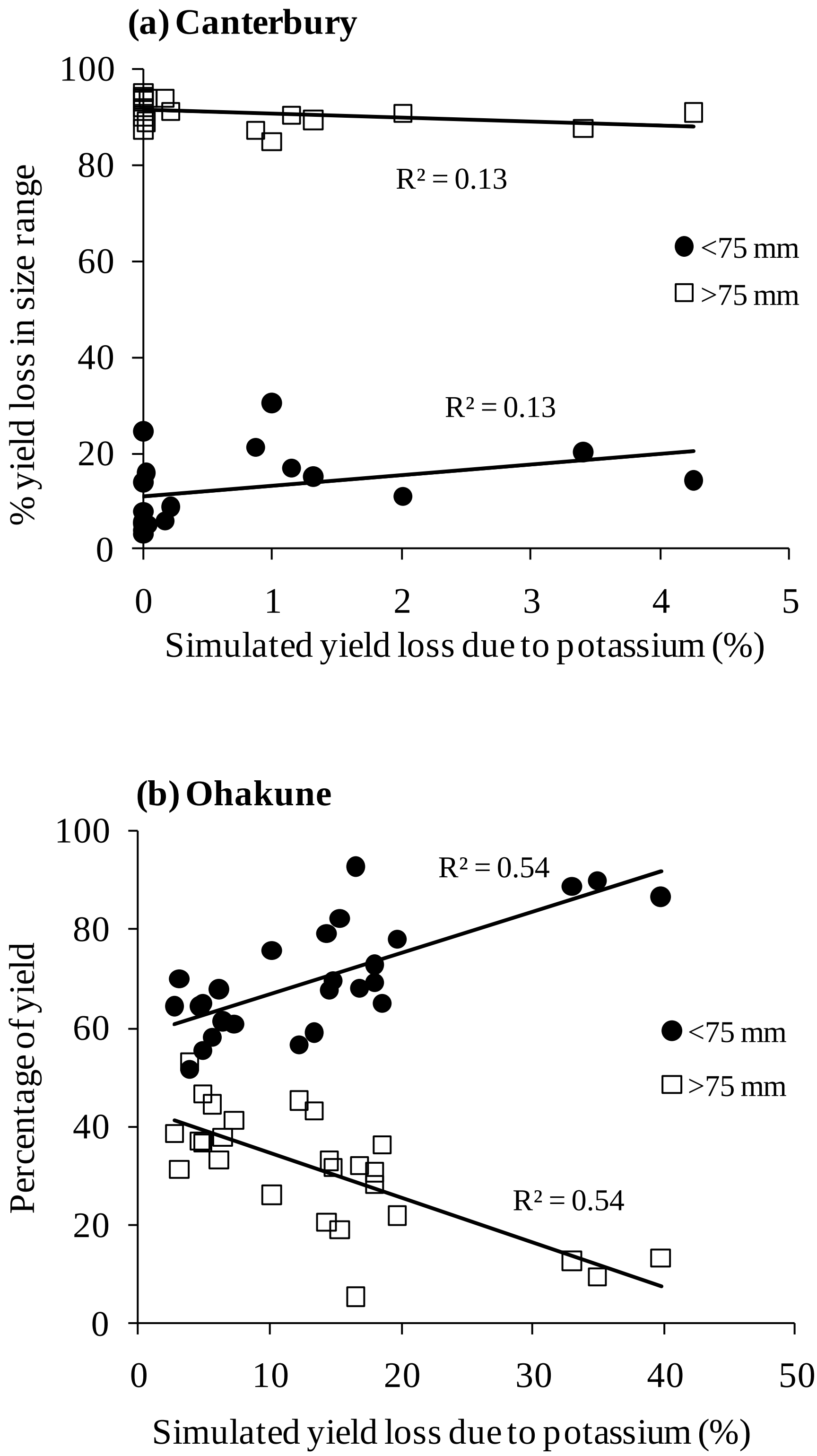

Figure 6: Relationship between simulated yield loss due to K and percentage of yield in tubers of size grades <75 mm and >75 mm for (a) experiments 4 and 5 in Canterbury and (b) experiments 6 and 7 in Ohakune.

Potassium supplies were generally good for the Canterbury sites (experiments 4 and 5) and the simulations suggest no substantial effect of decreasing K supply on either yield or tuber size distribution (Figures 2, 3 and 6). By contrast, K supply appeared to be more limiting to both yield and production of large tubers at Ohakune (Figures 2, 3 and 6). Indeed yield losses averaging 26% due to lack of K in the growers fertiliser regime were simulated at Experiment 7 (Figure 3). The supply of K was also strongly associated ($P<0.004$) with a decrease in tuber number at Ohakune, but not at the Canterbury sites (Table 4). The greater simulated supply of K at the Canterbury sites was most closely associated with the higher reserve K (TBK) values (Table 3).

No evidence was found to suggest that Mg supply limited yields at any of the sites, even for experimental treatments where Mg fertilisers were withheld. It appears that soil concentrations of Mg were adequate to meet crop demands.

It is important to note that the PARJIB analysis showed that for experiments 4 and 5, drought had a considerable influence on yield. We calculated the maximum potential soil water deficit (D_{max}) to be 116 mm for soils with an available water capacity (AWC) of about 85mm. The model indicated that this reduced yield by 23%. According to the PARJIB theory this would reduce the crops demands for nutrients by 23%. By contrast, D_{max} for experiments 6 and 7 at Ohakune was 86 mm on a soil with AWC of 330 mm. The PARJIB analysis suggested no water stress effects on yield in experiments 6 and 7, increasing the chances of observing yield responses to nutrient supply.

Discussion

Model calibration

In these experiments with potatoes, the PARJIB model accounted for 86% of the observed variation in yield, with a RMSE of 1.5 t ha^{-1}, or 13% of the average dry yield across a wide range of different sites, seasons, yields and soil types. Working with maize (*Zea mays* L.), Reid *et al.* (2002) found that PARJIB accounted for 83% of the observed variation in yield and the RMSE was 0.92 t ha^{-1} or 9.3% of the average (Reid *et al*., 2002). In combination with more detailed crop simulation models that can predict potential yields with N supply, PARJIB has performed similarly well with wheat (Jamieson *et. al.*, 2001).

The calibration took account of soil exchangeable and reserve K as well as P retention to result in an improved fit for different soil types. This reflects the observation that fertiliser recommendations for potatoes need to take into account soil reserves of nutrients (Craighead and Martin, 2003, Allison *et al*., 2001).

These results suggest that high reserves of exchangeable K contribute significantly to crop K nutrition and should be considered when making K fertiliser recommendations for potatoes. Previous research in the UK concluded that soil exchangeable K concentration is a poor predictor of potato K response (Allison *et al*., 2001) and this work confirms an advantage of soil tests which take account of more of the soil K reserve, such as the TBK test. Allison *et al*. (2001) also suggest that the release of K in the soil may be affected by management practices such as cultivar and irrigation practices and that this needs to be investigated.

The calibration accounts for planting dates from May through to November and accounts for a range of environmental conditions. However, the model needs to be calibrated and validated for a wider range of soil types to confirm the general results shown here. Cultural activities that may affect nutrient supply and release from soils should also be taken into account. The model could provide a useful analytical framework for analysing this sort of data.

Fertiliser practices

Analysis with the model showed that nutrient supply (from soil and fertiliser application) was limiting yield in most plots at the Ohakune sites, particularly by K. However, there was little effect at the Canterbury sites (Figure 3), where nutrient supply limited simulated yields by <9%.The PARJIB analysis indicated that in experiments 4 and 5 (in Canterbury) water stress reduced the maximum yield possible by about 23%, suggesting the model's prediction that this water stress response may have limited the response to fertilisers at these sites is correct.

Grower applications of N ranged from 260 kg ha^{-1} in Canterbury to 90 kg ha^{-1} in Ohakune. Overall, simulated yield losses due to inadequate N supply was less than 8% at the Canterbury sites - but more fertiliser may have been needed if water stress had been less limiting.

The model indicated there was still a small limitation due to insufficient P at Canterbury of about 3%, even though only about 60% of P needed for maximum yield was supplied to the crop (Figure 2 and 3). The simulated yield responses to N and P supply in Canterbury are a reminder of the diminishing returns style of yield response to nutrients that are often found in fertiliser experiments (Reid, 2002).

In Ohakune, insufficient K and to a lesser extent P and N supply appears to be the main reason for a yield loss (Figure 2 and 3). Work in the UK on soils with a wide range of soil P status suggested that the optimal P rates lie somewhere between 87-175 kg P ha^{-1} (Archer, 1988). Craighead and Martin (2003) showed that there were slight increases to P fertiliser application even for soil with Olsen P values higher than 29. For experiments 6 and 7, Olsen P values were 24 and 7 respectively and soil P retention values were high. At site 6, the application of 206 kg P ha^{-1} was optimal and with no yield loss due to insufficient grower P recorded (Figure 3). The 155 kg P ha^{-1} applied at site 7 was insufficient and resulted in a yield loss of 4%. Grower P rates were only slightly limiting in these soils. Tubers remove only about 0.5 kg of P t^{-1} and for a potential yield of 61 t ha^{-1}, this is a total removal of 30 kg P ha^{-1}. Efficiency of P fertiliser uptake is about 30 % (Craighead and Martin, 2003); significant reduction in P fertiliser supply could be obtained by improving the efficiency of P uptake by the plant.

Where application of fertilisers influenced yield it also affected the size distribution of the crop (Figures 4b, 5b and 6b). As fertiliser N, P and K rates increased and simulated yield loss was less, tubers tended to become more even in size. Rosen and Bierman (2008) found that for soils with high soil P values (25-33 mg kg^{-1} Bray P), applications of P increased yield but also increased the number of potatoes and resulted in more small tubers. They conclude that P nutrition plays an important role in regulating tuber set and this is confirmed by the data for our experiments (Table 4). Where the size distribution of the crop was influenced by nutrient supply in these experiments, there was also an effect on tuber number, suggesting a possible relationship between growth rate and tuber number. Managing crops for appropriate tuber size distributions required by the market requires an understanding of the when N, P and K nutrition affects tuber set and when it affects the rate of accumulation of tuber mass.

Potassium was only slightly limiting to yield at most sites (Figure 3), reducing yields by less than 5%. This is consistent with observations of Allison *et al*. (2001), that largely potato crops are unresponsive to K fertiliser; the exception is where soil K levels are low or there is an absence of irrigation. The exception to this was in Experiment 7, where TBK was very small (0.07 meq kg^{-1}) and where inadequate K supply did appear to affect yield substantially under the growers' fertiliser regime. Exchangeable K levels and K application rates were similar between experiments 5 and 7 (Table 2 and 3), yet the response to K was different. This suggests the difference is probably due to differences in the levels of TBK.

The analysis conducted here only shows what standard grower practices are and identifies where nutrient limitations may occur. A strong economic analysis would dictate the value of increasing fertiliser applications, together with leaching potential for given fertiliser applications.

Conclusion

The PARJIB model calibrated well for potatoes over a wide range of conditions and yields. The model can be used to optimise pre-season planting based on soil tests and likely weather conditions.

The examination of the current fertiliser practice at the Canterbury and Ohakune sites in this study showed that N and P applications are unlikely to be limiting yields greatly. The supply of K may be limiting to yields at the Experiment 7 site at Ohakune. In Ohakune, N, P and K supply affected both tuber yield and size distributions. Drought was more limiting to yields than nutrients in our experiments in Canterbury.

The PARJIB model provides a useful framework to interpret nutrient effects on yield, identifying which nutrients are limiting yields most, or if other factors are limiting crop response to nutrients. As an analytical tool it has the potential to extend our understanding of crop responses to nutrients.

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