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Defining the relationships between pasture production and soil P and the development of a dynamic P model for New Zealand pastures: a review of recent developments

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Abstract A database was constructed comprising records from 2255 pasture phosphorus (P), potassium (K) and sulphur (S) field trials, of which 1799 included one or several rates of P. Subsets of this data were selected based on predetermined criteria to define the relationships between relative pasture production and available soil P (0–75 mm, Olsen P in $\mu g\ P\ cm^{-3}$ soil)—the P production functions—for the major soil groups in New Zealand. These relationships, and their 95% confidence intervals, were defined using Bayesian statistics. For those soil groups for which there was sufficient data, the production functions were well defined and gave reasonably precise estimates of the relative pasture yield for a given Olsen P. For example, for the volcanic soils, the relative pasture production is most likely ($P < 0.05$) to be in the range 88–94% at Olsen P 25 and 98–100% at Olsen P 50. The shape of the production functions was similar for all soil groups—the relative pasture production increased with increasing Olsen P up to an asymptote—except the pumice soils and the podzols, which showed irregularities. The production function for the podzols was also flatter. There was good agreement between the empirically derived production functions and those generated from a dynamic P model. The Olsen P level required to achieve 97% maximum production was estimated for all soil groups. These ranged from 10 to 45 depending on soil group. The critical Olsen P levels were related to the soil anion storage capacity (ASC, a laboratory measure of P buffer capacity) and to soil volume weight (g cm^{-3} of sieved and dried soil), although not strongly. The field measured P buffer capacity (ΔP_F)—the amount of soluble fertiliser P (kg P ha^{-1}) required above maintenance to increase the Olsen P (0–75 mm) level by 1 unit—was estimated for selected trials. There was reasonable agreement between these estimates and those derived from the P model (ΔP_M), and these results indicated that ΔP decreases with increasing Olsen P. The results imply that factors other than those related to soil chemical properties affect the relationship between soil P and pasture production. The factors which determine the relationship between pasture production and soil P are defined and discussed. These were assigned to two categories: those factors which affect the ability of the soil to supply P for plant uptake and those that affect the ability of the plant to acquire soil P. It is concluded that further progress towards improving our ability to predict pasture responses to fertiliser P will depend on quantifying the latter effects. Based on these results and the development of a dynamic P model, an econometric P model was developed for New Zealand pastures which enables consultants to quantify the likely agronomic, financial and investment effects of any given fertiliser strategy on a given farm or block within a farm. This was not previously possible but is essential for the sustainable use of P fertilisers in pastoral farming.

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INTRODUCTION

Phosphorus (P) is not only the most expensive macro-nutrient applied to legume-based pastoral soils, it is also a major pollutant, affecting water quality. For these reasons, sound, objective advice on the use of P fertilisers is essential for both financial and environmental reasons. To achieve this, it is first necessary to understand and define, as accurately as possible, the relationship between pasture production and available soil P. Once the production function is defined it is possible to determine, for a given farm, the economic optimal soil P level (Metherell et al. 1995). Thus the balance between economic viability and environmental compliance can be more objectively assessed as required for sustainability, applying the Framework for the Evaluation of Sustainable Land Management (FESLM) definition (Symth & Dumanski 1994).

Much of the earlier research in New Zealand (Grigg 1968, 1972, 1977; Sherrell 1970), conducted in both glasshouse and field experiments, was directed at defining which of the many tests developed internationally for measuring plant available soil P was most appropriate for New Zealand's conditions, and in particular the chemistry of New Zealand soils. This research, together with the more comprehensive study by Saunders et al. (1987) concluded that a modified Olsen test (Olsen et al. 1954), based on extracting a volume rather than a weight of soil (dried and sieved soil and Olsen P = $\mu g\ P\ cm^{-3}$ soil), gave the best correlation with either plant yields or plant P uptake. This was so despite the fact that it was originally developed for alkaline soils and that most New Zealand soils are acid (mostly pH < 6.0). The reason for the apparent contradiction is that many New Zealand soils are derived from recent sedimentary materials and contain significant quantities of apatite minerals containing P, not available for plant uptake, but soluble in an acid extract such as the Truog test (Truog 1930) (Grigg 1968, 1972, 1977).

More recently the focus has been on quantifying the relationship between pasture production and soil Olsen P. Saunders et al. (1987) reported results from a series of 62 pasture field trials measuring the effect of rates of P fertiliser on pasture production and Olsen P, and covering a wide range of soil groups. They recorded that the correlations between relative pasture production and soil P, using a polynomial function, were generally low ($R < 0.30$), although higher correlations ($R > 0.8$) occurred at some times on some sites. This latter point is consistent with reports of reasonably high correlations between pasture production and Olsen P when the experiments are restricted to one site (e.g., Grigg 1977; McCall & Thorrold 1991) or a few sites on the same soil group (e.g., O'Connor & Gray 1984; O'Connor et al. 2001). Given these difficulties, Saunders et al. (1987) suggested a different approach. They defined a term, probable minimum yield (PMY), as the relative yield below which the observed relative yield will fall 20% of the time, for a given soil test level. Using this probability approach they found high correlations with soil P levels (i.e., for Olsen P on a volume basis, $R^2 > 0.80$).

Sinclair et al. (1997) analysed 46 datasets, derived from 17 long-term (4–6 years) field trials comparing rates of P, using a Mitscherlich function, and found that overall this accounted for only 27.6% of the variation between relative yield and Olsen P. More importantly, they were able to examine the components of the variation in the relationship between relative yield and Olsen P. They found that the largest source of variation was within-a-site × within-a-given year, followed by within-site × between-year variability. The between-site variability was relatively small.

In all these studies the approach has been to fit known mathematical functions to the data. This assumes that something is known *a priori* about the nature of the relationship between pasture production and available soil P. An alternative approach is possible using Bayesian statistics (Upsdell 1994). This allows the most probable relationship between two variables (and the confidence interval) to be determined without the need to make assumptions about the form of the relationship. This approach has been applied to data stored in an electronic database summarising the results from fertiliser P field trials conducted in New Zealand over the period 1940–90. These generalised functions, and the associated 95% confidence intervals for the major soil groups in New Zealand have been informally published (Morton & Roberts 1999; Roberts & Morton 1999), together with information on the soil P buffer capacity (ΔP_F, i.e., the amount of fertiliser P (kg P ha^{-1}) required above maintenance to change the Olsen P in the field by 1 unit). Also, data from these field trials was used to develop a dynamic P model (Metherell et al. 1995) from which the economic outcomes from different fertiliser strategies could be calculated at the farm level. This model has undergone minor revision. The purpose of this paper is to record and discuss these developments in the scientific literature.

METHODS

Description of database

Commencing in the late 1940s, many field trials were conducted by the then Department, and laterly the Ministry, of Agriculture to measure the effects of fertiliser P, K, and S (including rates, form and timing of applications) on pasture production. These trials were conducted using established standard field techniques as documented by Lynch (1966). A major initiative was commenced in 1990 (Edmeades 1995) to capture and record all this information to preserve it for posterity and to facilitate access to it for future scientific purposes. For this purpose a SIR electronic database was established with very detailed and specific schema (Feyter 1993). In brief, the following information was recorded for each trial: site history, topography, aspect and soil group; pasture type and composition; farm type; trial design and treatments, including basal applications of nutrients; commencement date and duration and the pasture measurement technique. Within each trial, the treatment effects on pasture and animal production, botanical composition, pasture and soil nutrient concentration, and any visual assessments, were recorded, if available, at the individual harvest or measurement level. To preserve the integrity of the information, the residual degrees of freedom, derived from the overall analysis of variance of the trial was recorded, together with a subjective assessment of the reliability of the trial. If the trial appeared to be professionally conducted throughout its duration with few unforeseen problems it was judged superior and given a rating of 1, if problems arose that may have affected the veracity of the results it was given a "problem" category (3), otherwise it was rated as average (2). Trials from all categories were used in the calculations reported in this paper.

In total, results from 2255 P, K, and S trials were recorded of which 1799 included one or several rates of P. The effect of treatment on pasture production was measured (as distinct from visual assessment) on 1270 trials, and of these, 29 trials included treatment × animal production records. These P trials were distributed geographically as follows: northern North Island (493), southern North Island (488), northern South Island (231), southern South Island (579).

There were no reliable trial data for the peat soils at the time the database was established. Subsequently, a series of trials has been completed on these soils (O'Connor et al. 2001). The key results from this series of trials are included in this review where appropriate.

Selection of trials and analysis

For determining the relationships between relative yield and Olsen P (μg P cm^{-3} soil, 12 months following fertiliser applications) only those trials were extracted from the P database which had at least four rates of soluble fertiliser (possibly including zero), in which pasture dry matter (DM) was assessed under continuous cutting, and in which there were no other nutrients limiting pasture growth. These trials also had to have a corresponding Olsen P soil test (0–7.5 cm depth) on a per treatment basis at the end of the year. The end-of-year Olsen P values were used as they reflected the effect of fertiliser P, and hence pasture production, during the previous 12 months. The asymptotic production was estimated using the Bayesian smoothing program Flexi (Upsdell 1994), and the relative yields obtained. For a given soil type classification, the relative yields were then plotted against the Olsen P soil tests and the spline with its 95% confidence interval was estimated using Flexi.

For estimating ΔP_F values only those trials with Olsen soil tests (0–7.5 cm depth) on a per treatment basis for at least 2 years were used. Each trial had to have a minimum of four rates of soluble P fertiliser, possibly including zero. Virtually all trials had a pre-trial soil test. As the relationship between soil test and time for a given rate of fertiliser is not linear in the long term (over the years of the trial), the data used for this assessment was limited to a maximum of 2 years. Based on previous experience, the following model was fitted to the data for each trial using Genstat (2005): Olsen P (year, rate) = $a + b \times$ time $+ c \times$ rate × time, where a and b are constants and parameter c is the estimate of ΔP.

Phosphorus model

A dynamic P model for pastures under grazing has been developed and the essential components of the initial model are described elsewhere (Metherell et al. 1995). Some improvements have subsequently been made. The model is based on a conceptual labile P pool (kg P ha^{-1}), the size of which was derived by fitting the model to Olsen P (at the beginning of the year) and relative yield data from small plot field trials where inputs (in fertiliser) and outputs (in herbage cuttings removed) of P were known. Parameters fitted were a soil loss factor and the relationship between labile soil P and Olsen P. An extended model including a Mitscherlich curvature coefficient was then fitted to the relative yield data. A slow soil input of 3 kg P ha^{-1} was assumed for all soil groups based on modelling of data from a long-term trial at Winchmore (Metherell et al. 1995). In the initial model development (Metherell et al. 1995) a linear relationship was assumed, however for some very good datasets (Morton et al. 1999) where there was no return of clippings and high P removal, negative soil P was predicted for the control treatment. In fact only a small decline in Olsen P had been observed over 8 years. A similar observation of little decline in Olsen P with no fertiliser input was also seen in the Winchmore long-term grazing trial control treatment (Metherell 1994). To overcome this problem a curvilinear relationship between Olsen P and labile soil P (kg P ha^{-1}) was required. A power function (Eqn 1) was fitted (Metherell et al. 1995), where *g* and *f* are parameters.

A curvilinear relationship between Olsen P and labile soil P (kg P ha^{-1}) was required

$$\text{Soil P} = \left(\frac{\text{Olsen P}}{\frac{200^{(1-g)}}{f}} \right)^{\frac{1}{g}} \quad (1)$$

Equation 1 was originally formulated so that if $g = 1$, then $\Delta P = f$ and different values of *g* will always give Soil P = 200 at an Olsen P value of 200/*f*.

ΔP is the additional fertiliser P required (kg P ha^{-1}) over and above the maintenance requirement, to increase the Olsen P soil test by 1 unit. (This is when the relationship is formulated as a differential equation (see Eqn 2) and also disregards the effect of an increase in soil P status on the maintenance requirement.)

ΔP_M is a function of Olsen P, decreasing as Olsen P increases.

$$\Delta P_M = \frac{\partial \text{ soil P}}{\partial \text{ Olsen P}} = \frac{200^{\frac{(g-1)}{g}} \times (f \times \text{Olsen P})^{\left(\frac{1}{g}\right)}}{g \times \text{Olsen P}} \quad (2)$$

The fitting procedure primarily used about 20 "elite" field experiment datasets from the database which had time series of soil test and yield data for five or six fertiliser rates. The model fitted involved estimation of P inputs from fertiliser (known) and slowly available soil pools (linear), losses of P in soil processes (linear) and herbage removal (known), calibration of the relationship between Olsen P soil test and "labile" soil P (non-linear), and a relationship between soil P and relative pasture yield (non-linear). The major problem was partial correlation of model parameters, such that two or more parameters could be changed simultaneously with only a small impact on the goodness of fit. The fitting method used a procedure involving multiple simulations using a 2D or 3D grid of parameters in the space of interest. For each simulation an objective function was calculated as the sum of absolute deviations of estimated to measured data points. The analysis of the objective function was done by plotting the contour surfaces of the goodness of fit. At that stage, various surfaces were compared and combined and judgments made about groupings of datasets and the best combinations of parameters. As a check on the procedure, simple plots of the predicted and observed time series of yield and soil test data were made. The least satisfactory aspect of the procedure was that when fitting the model to both soil test and pasture data it was necessary to make a judgment about the weighting of deviations from Olsen P compared to deviations in relative yield.

Considering the limitations of the datasets, available trials were grouped into four sets representing sedimentary soils, pumice soils, other soils derived from volcanic parent materials, and a group containing soils which had higher rates of soil P loss, mainly containing podzol soils. (See Roberts & Morton (1999) and Morton & Roberts (1999) for a brief description of these soil groups.) It was assumed, based on their properties (i.e., bulk density, soil P chemistry) and on previous field experience, that the within-group variability was less than the between-group variability. The relationships between Olsen P and labile soil P for each of these four sets of soils are shown in Fig. 1A–D.

A major outcome of the fitted model was that, once the soil group effect on the Olsen P-labile soil P relationship had been taken into account, all soil groups had the same relationship between labile soil P and relative pasture yield.

PASTURE PRODUCTION FUNCTIONS

The relationships between relative pasture production and Olsen P, and the associated 95% confidence interval, for those soil groups for which there was

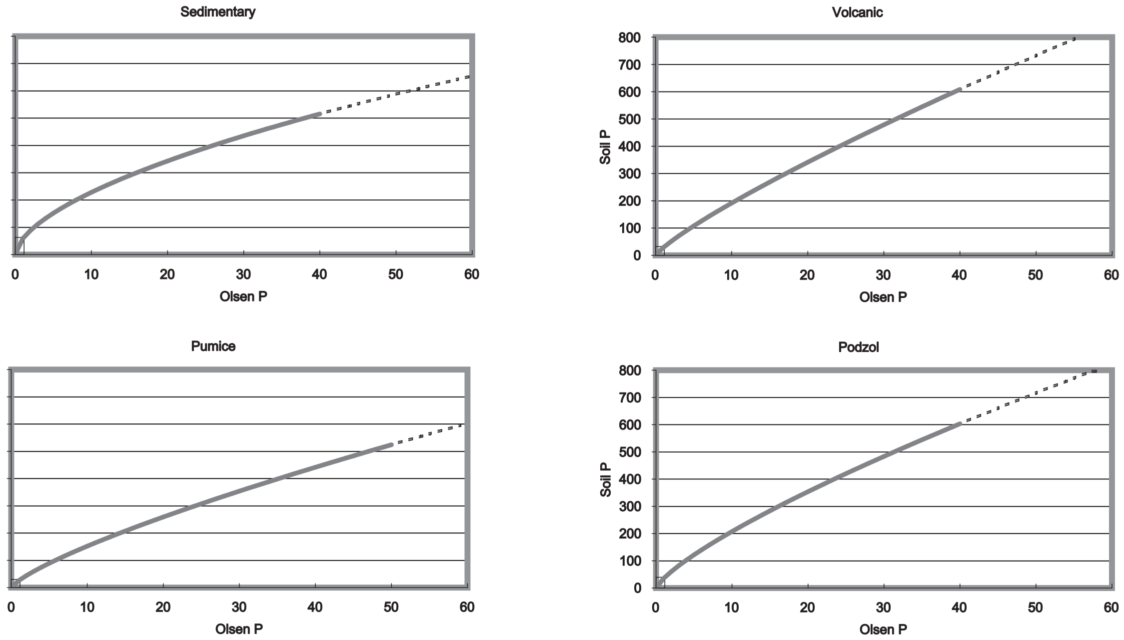


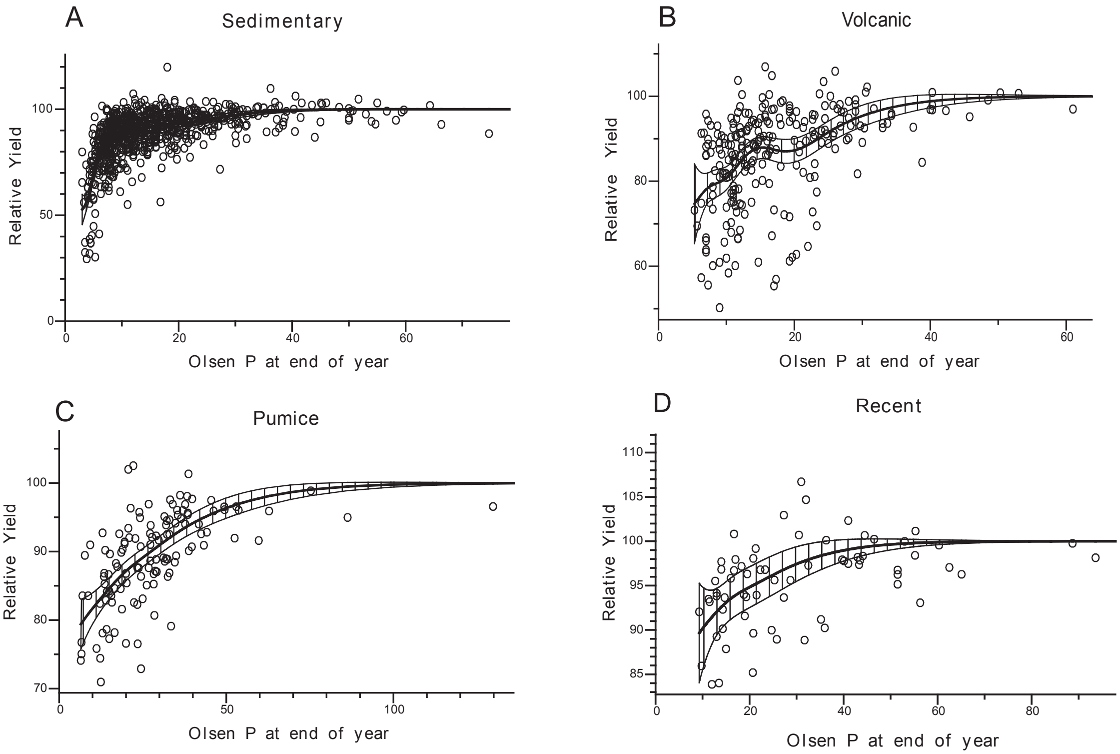
Fig. 1 The relationships between Olsen P (0–75 mm, μg P cm^{-3} soil) and a conceptual pool of labile P (soil P in kg P ha^{-1}) for four major soil groups in New Zealand as used in a dynamic P model (Metherell et al. 1995).

Table 1 Estimated relative pasture production at Olsen P (0–75 mm, μg P cm^{-3} dried and sieved soil) levels of 25 and 50 and critical level required to achieve 97% maximum production, for the major soil groups in New Zealand (numbers in brackets are the confidence intervals ($P < 0.05$)).

Soil group	Relative pasture production		Critical level
	Olsen P 25	Olsen P 50	
Pumice	89 (88–91)	97 (95–98)	50 (43–61)
Volcanic	92 (88–94)	99 (98–100)	32 (27–38)
Peat[1]	95	99	40 (35–45)
Sedimentary	95 (93–97)	100	30 (26–32)
Recent soils	97 (96–98)	99 (98–100)	25 (20–30)
Podzols	96 (94–99)	100	25 (22–30)
Sands	100	100	12 (10–15)

[1]From O'Connor et al. (2001).

sufficient data, are given in Fig. 2A–F. Quite clearly, there is considerable variability in the relationships between relative yield and Olsen P, as noted by Saunders et al. (1987) and Sinclair et al. (1997). In all cases the size of the confidence intervals decreases as the Olsen P level increases, a feature noted by Saunders et al. (1987) (see Fig. 2 and Table 1). However, this Bayesian-statistical approach defines the most probable ($P < 0.05$) relative yield, at a given Olsen P level, for a given soil group. The most probable relative yields at Olsen P 25 and 50 and the Olsen P at a relative yield of 97%, typically referred to as the "critical level" are given in Table 1 for each soil group. As indicated by the size of the confidence intervals, these relationships provide a reasonably precise estimate of relative yield for a given Olsen P. For example, for the volcanic soils, the relative pasture production is most likely ($P < 0.05$) to be in the range 88–94% at Olsen P 25 and 98–100% at Olsen P 50.



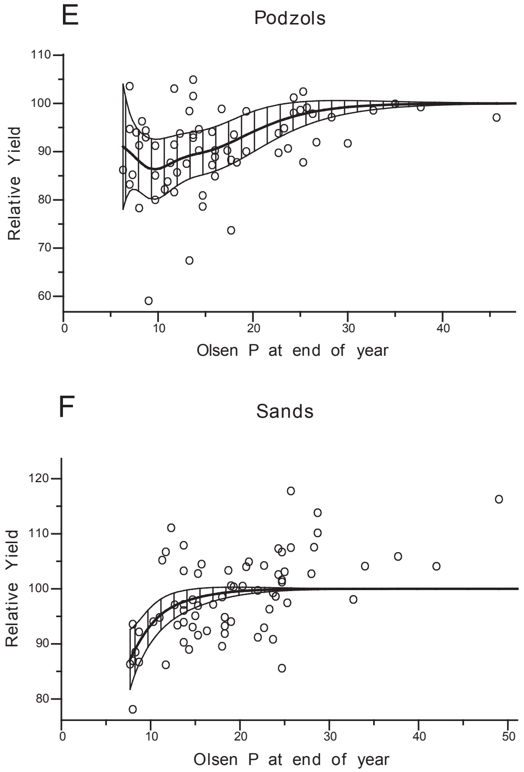


Fig. 2 Relationships between relative pasture production and Olsen P (end of year, 0–75 mm, µg P cm^{-3} soil), and confidence interval ($P < 0.05$), for pasture trials in New Zealand on **A**, sedimentary soils; **B**, volcanic soils; **C**, pumice soils; **D**, Recent soils; **E**, podzols; and **F**, sands.

For all soil groups, the most probable relative yield increases with increasing Olsen P up to an asymptote. For both the volcanic soils and the podzols there are irregularities. It is unlikely that these irregularities have any biological meaning—they simply reflect the intrusion of uncontrolled variability. This being the case, and given the nature of Bayesian statistics, it is likely that these irregularities would be smoothed out by the addition of more trial data. The podzol production function is also relatively flat. It is possible that this is because most of these soils have very little capacity to retain P (anion storage capacity (ASC) <20%). Thus, pasture production on these soils depends largely on external applications of fertiliser P, rather than the supply of soil P.

The relationships between relative pasture production derived from the field trials and predicted by the P model are shown in Fig. 3. Allowing for experimental error there is good agreement. It must be noted, however, that some of the field trial data in Fig. 2 was also used to develop components of the model. However, Roberts et al. (1995) provided further independent evidence as to the accuracy of the model by comparing Olsen P levels measured annually at 89 sites throughout New Zealand over a 5-year period with those predicted by the P model, using input data from each site. They found that the distribution of the deviations for observed and measured Olsen P were normally distributed around zero, indicated no bias, and that observed values differed from predicted values by between 1 and 5 Olsen P units. They suggested that these differences were more likely to result from random spatial and temporal variability in the Olsen P test (see Edmeades et al. 1988) rather than inherent errors in the P model.

It is reasonable to conclude that the use of Bayesian statistics to define the average relationship between pasture production and Olsen P at the soil group level has been successful in this study, but it does depend on the existence of sufficient data. This approach overcomes the pressing practical problem of predicting relative pasture production from soil fertility tests. However, it does not advance our understanding of why there is so much variability in pasture production versus soil test relationships, at least as measured in the field. This is an important issue which will be discussed later.

The same statistical approach has now been used to define the production functions for S (Morton & Roberts 1999; Roberts & Morton 1999; Edmeades et al. 2005) and K (Morton & Roberts 1999; Roberts & Morton 1999), for New Zealand soils.

CRITICAL P LEVELS

The critical Olsen P levels (Olsen P required to achieve 97% relative yield) for each soil group, including the peats (O'Connor et al. 2001), are given in Table 1. (Note that the choice of 97% relative yield to define the critical levels is somewhat arbitrary. It has been used for convenience here so that these current results can be compared with the earlier estimates of Morton & Roberts (1999) and Roberts & Morton (1999).) They range from 50 to 12 in the order: pumice > peats > volcanic > sedimentary > podzols = recent > sands. There is a trend for the critical levels to increase with ASC (Fig. 4) but the relationship is not strong. (Note than the ASC levels on the individual trials were not measured and hence the middle of the ASC ranges for each soil group given by Saunders (1968) (and see Table 2), were used in Fig. 4). This trend is consistent with the results published by Helyar & Spencer (1977) for a set of 51 trials in New South Wales, Australia. However, in both studies the relationship is not strong. A further complication arises because in New Zealand soils are assayed for routine advisory purposes on a volume basis (after drying and sieving in the laboratory—this should not be confused with the field measurement of bulk density) rather than a weight basis. Rajendram et al. (2003) showed that the Olsen P concentration in a given assay based on soil weight

Table 2 Estimated soil phosphorus (P) buffer capacities (ΔP_F, the amount of soluble P (kg P ha^{-1}) to increase Olsen P by 1 unit) derived from field trials and from the P model (ΔP_M), and the anion storage capacities (ASC) (formerly phosphate retention), for the major soil groups in New Zealand. (Listed in decreasing order of ASC.) nd = not determined.

	ΔP_F		ΔP_M	ASC[1]
Soil group	No. trials	Median and range	(range[2])	(%)
Volcanic	16	12 (4–36)	(12–17)	80–100
Pumice	10	7 (4 –11)	(8–12)	40–60
Peats	8	6–9[3]	nd	29–89
Sedimentary	81	8 (2–40)	(7–45)	20–50
Recent	6	4 (2–12)	nd	0–30
Sands	3	16 (15–24)	nd	0–30
Podzols	4	9 (8–11)	(12–17)	0–30

[1]Method and range as per Saunders (1968).
[2]Depending on Olsen P level (see Fig. 5).
[3]Depending on ASC (see O'Connor et al. (2001).)

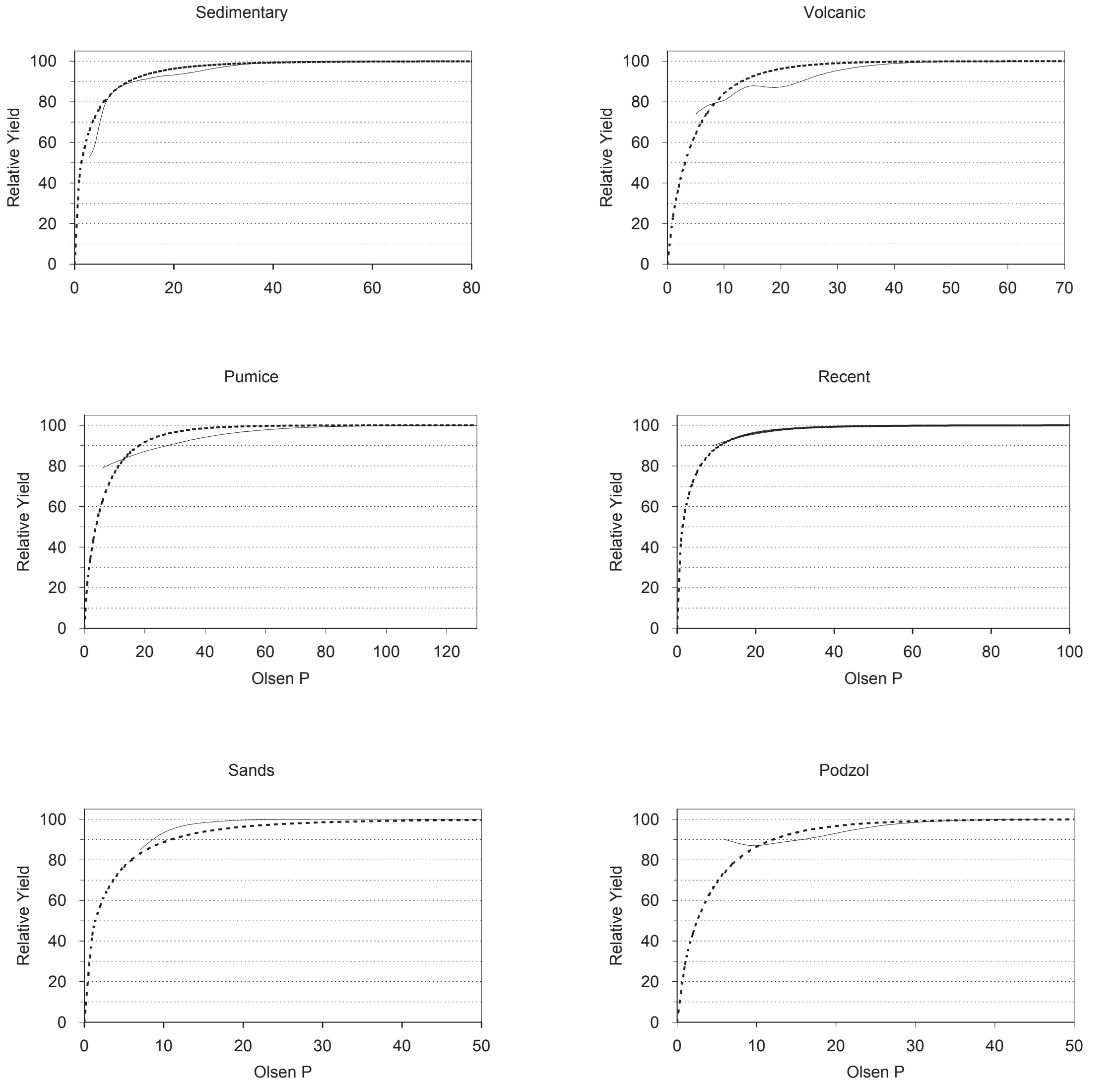


Fig. 3 The relationships between relative pasture production and Olsen P as determined by a dynamic P model (dotted line) and empirically from field trial data (solid line) (see Fig. 1 and 2).

increases with decreasing volume weight. They reported the median and range in the volume weight of 100 New Zealand topsoils as follows: peats 0.58 (0.46–0.75); volcanic 0.67 (0.50–0.92); pumice 0.70 (0.65–0.93); and sedimentary 0.84 (0.75–1.63). Although this does not exactly match the trend in the critical Olsen levels, it is reasonable to suggest that soils with low volume weight (as measured in the laboratory) have higher critical Olsen P levels.

Based on an initial analysis of the data in the database, Morton & Roberts (1999) and Roberts & Morton (1999) estimated the critical Olsen P levels for 97% maximum production to be 38, 22, and 20 for the pumice, volcanic, and sedimentary soils respectively. These are slightly less than those reported in Table 1. The likely reason for this is that more rigorous protocols were applied to selecting the current datasets.

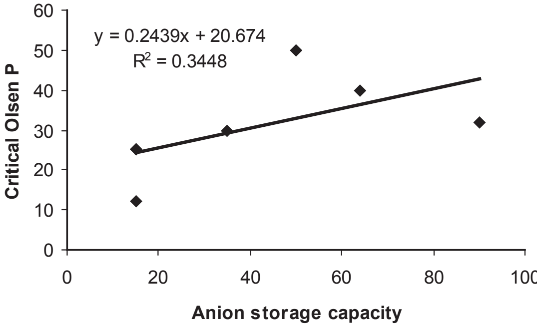


Fig. 4 The relationship between the critical Olsen P (Olsen P required to achieve 97% maximum production) and the anion storage capacity (ASC) (formerly phosphate retention (Saunders 1968)). The values plotted are the middle of the ranges given by Saunders (1968) for each soil group, see Table 2.

P BUFFER CAPACITY

Changing from one state to another on the P production function requires knowledge of the soil P buffer capacity (ΔP)—the amount of soluble fertiliser P (kg P ha^{-1}) over and above maintenance required to increase the Olsen P by 1 unit in the field. The ΔP values derived from the field trials (ΔP_F), and the associated Olsen P level of the trial, are shown in Fig. 5 together with those generated by the P model (ΔP_M).

For the volcanic, pumice, and sedimentary soils there is general agreement between the estimates derived from either the P model or the field data, in the sense that the ΔP values decrease as the Olsen P level increases. Increasingly less amounts of soluble P are required to increase the Olsen P level as the initial Olsen P level increases. However, the field data are variable. The field determined ΔP values include factors which are not included in the P model estimates, including the incorporation of fertiliser P into the soil organic matter and all the factors which affect the temporal and spatial variability in Olsen P. In addition, the model may not be accurately reflecting soil P losses, especially if these are site specific. There is, however, reasonable agreement between the median field values and the predicted model values, allowing for the inherent variability in the data (Table 2). The exception is the podzols for which the field derived ΔP are lower for all values of Olsen P than those derived from the model.

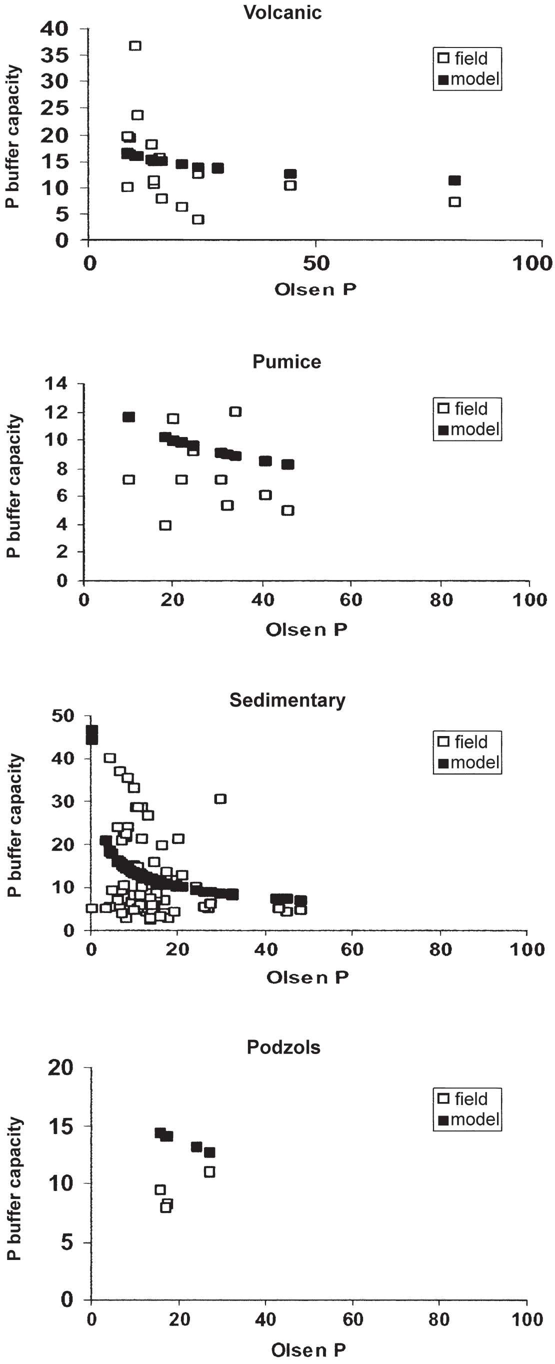


Fig. 5 Relationship between P buffer capacity (ΔP, the amount of soluble P (kg P ha^{-1}) required to increase the soil Olsen P (0–75 mm) level by 1 unit) and Olsen P for the volcanic, pumice, sedimentary soils and podzols as determined from field measurements (ΔP_F, open symbols) and a dynamic P model (ΔP_M, closed symbols).

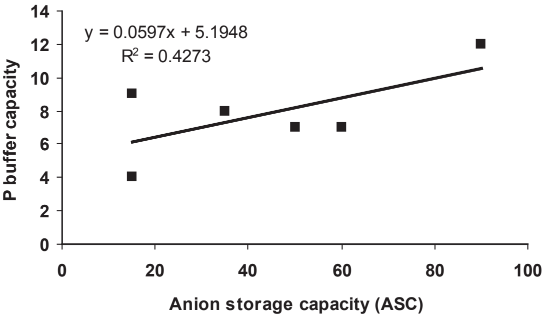


Fig. 6 Relationship between soil anion storage capacity (ASC) and field measured median P buffer capacity (ΔP_F, kg P ha^{-1}). The values plotted are the middle of the ranges given by Saunders (1968) for each soil group, see Table 2.

This suggests that the P model is systematically overestimating the P buffer capacities on this soil group.

In practice, the use of an imprecise measure of ΔP could result in either over- or underestimating the amounts of capital fertiliser P required in a given situation. This risk can, however, be managed and minimised by taking a cautious approach and having a good soil testing protocol in place to monitor changes in soil Olsen P over time, as is becoming standard practice in New Zealand.

Leaving out the sands, there is a trend for ΔP_F to increase with ASC, as might be expected. However, this relationship is tenuous (Fig. 6) ($R^2 = 0.4$), taking into account the variability in the data. This lack of a strong relationship is consistent with the results reported by Fleming et al. (1997). They used a number of different laboratory tests to measure the soil buffer capacity of a series of 27 rates of P pasture trials in Australia and found that they were not related to the field determined P buffer capacity. The likely reason for this is that ΔP_F is the net result of many soil processes over time including the incorporation of fertiliser P into organic matter and the various P losses. A laboratory measurement does not account for these factors.

The ASC test developed by Saunders (1968) is related to the amount of Fe and Al in the soil and is used in New Zealand as a guide, along with other information, to decide which soil group, and hence which production function, should be used in a given situation, for the purposes of giving fertiliser advice. However, the laboratory buffer tests examined by Fleming are not related to organic matter, soil texture, clay or Fe content (Fleming et al. 1997). This raises an interesting issue: what is the utility of such methods?

In contrast to New Zealand soils, Australian pastoral soils have low ASCs and low ΔP. In a set of 90 pastoral soils (Burkitt et al. 2002), 50% were <20 and 80% <30 using the New Zealand method of Saunders (1968), as discussed elsewhere (Edmeades et al. 2003). Similarly, ΔP_F values measured in the field on 27 representative sites are also lower than found in most New Zealand soils (mean 4.8 (range 2.2–12.5) kg soluble P ha^{-1} per unit increase in Colwell P test (Fleming et al. 1997); this equates to approximately 1 (0.5–3.2) kg soluble P ha^{-1} per unit increase in Olsen P (see later for conversion factor).

Figure 7 shows the relationship between relative pasture production and Colwell P derived from a set of data from published and unpublished rates of P trials (78) on pastures in New South Wales in Australia, covering three major soil groups. The Colwell P test is a modification to the Olsen P test (Colwell 1963) and appears to be a reasonable predictor of relative pasture production across these three soil groups. Analysis of this data using Bayesian statistics indicates that there is no significant ($P < 0.05$) difference in the relationships between the soil groups. The Colwell P associated with a relative yield for 97% maximum production is about 50. This is consistent with Helyar & Spencer's (1977) results, also from New South Wales, suggesting that the critical Colwell P levels ranging from 22 to 48 depend on soil buffer capacity. Based on correlations between Colwell and Olsen P across the same set of soils as in Fig. 7, a critical Colwell P of 50 equates to an Olsen P of 12–13 (Olsen P = 0.26 × Colwell P), suggesting that this set of Australian soils behave similarly to the New Zealand sands with respect to their low ASC and low critical Olsen P. The apparently high ΔP values for the sands, albeit on only three sites, is, however, anomalous. This result is tentative and further analysis is required based on larger sets of data.

Taken together, these trial data from New Zealand and Australia suggest that the relationships between pasture production and soil P for different soil groups are similar in general shape but differ in respect to their displacement on the *x*-axis. In other words, the critical soil P level can be, but not always is, different for widely disparate soil groups in terms of their chemical, biological and physical properties. Such differences are normally attributed to soil P buffer capacity (Helyar & Spencer 1977; Holford

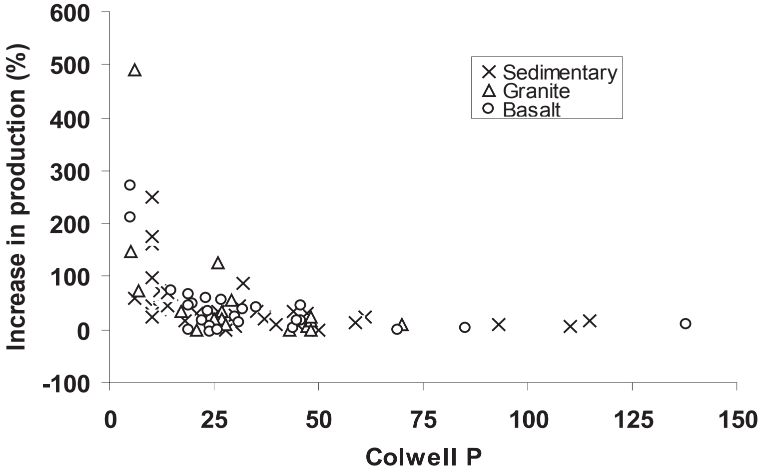


Fig. 7 Relationship between pasture response to P (% increase over the control for the highest yielding P treatment) and Colwell P for a set of published and unpublished rates of P trials in New South Wales, Australia, covering a range of soil groups.

1997). This does not appear to be the case for this set of New Zealand trial data. However, there is evidence from this study that the critical P level may be associated with ASC and/or soil volume weight. If it is assumed that these two soil properties are independent, and this may not always be the case (see Tables 1 and 2), it can be speculated that the relationship between pasture production and soil P is not determined solely by soil chemical properties but by the physical environment of the plant. This suggestion also comes from the work of Sinclair et al. (1997).

COMPONENTS OF THE P PRODUCTION FUNCTIONS

Sinclair et al. (1997) analysed the results from 17 long-term field trials conducted under controlled and uniform conditions. They reported that the sources of variation in the relative pasture production versus Olsen P relationships were, in order of size: within years within sites > between years within sites >> between sites. In other words, most of the variability arises within a year at a given site. They also listed some of the factors which can give rise to the variability in these relationships. Their conclusions are important and deserve elaboration:

The P production function in perennial clover-based pastoral soils can be formalised as follows, assuming that P deficiency is the only nutrient limiting production:

Relative pasture production = *f* (available P)

Available P = *f* (soil factors which affect the plant availability of soil P) + *f*(plant factors which affect the plant's demand for P and ability to access soil P).

Soil factors = *f* (amount of labile inorganic P, rate of P diffusion, vertical and horizontal distribution of soil P, phosphate buffer capacity, mineralisation and immobilisation of organic P, soil moisture and temperature, soil parent material and texture).

Plant factors = *f* (pasture species and composition, root structure, growth rate, defoliation frequency and time, the presence of mycorrhiza and nematodes, soil moisture and temperature).

To these must be added those factors which affect the measurement of relative pasture production:

Relative pasture production = *f* (field measurement technique [including defoliation severity and frequency, grazing versus mowing influence] and statistical techniques [e.g., experimental design, model used and estimation of maximum yield]).

Sinclair et al. (1997) suggested that the major sources of variation can be summarised as the temporal variations in Olsen P (i.e., the soil factors) and pasture responsiveness to applied P (the plant factors), which are uncontrollable in the normal field situation. For instance Edmeades et al. (1988) reported that the temporal variability in Olsen P was about 20% and was unpredictable across sites and seasons. Roberts (1987) found that variations in Olsen P were not related to pasture production, suggesting that soil P supply and pasture P responsiveness are unrelated.

Given that the measurement of available soil P is only one of many factors which determine the P production function in the field, it is not surprising that soil tests only account for a small proportion of the variation. In the glasshouse, some, but not all, of these sources of variation are removed or reduced and it should be no surprise that under these circumstances a higher proportion of the variability can be accounted for (Sherrell 1970).

This general conclusion has important implications. First, as Sinclair et al. (1997) concluded, ".......even a 'perfect' test [soil P test], measured with utmost precision, may be unable to account for more than a small fraction of the variability in response to fertiliser [P]." In addition, it is predictable that most soil P tests, at least those that are surrogates of the same soil P pool, will be equally effective predictors of pasture production, allowing for experimental error. If this is so then it appears that further progress towards refining and understanding the nature of P production functions will depend on further understanding of how plants acquire soil P, rather than trying to find a new test for available soil P.

ECONOMIC ANALYSIS OF FERTILISER P REQUIREMENTS

The primary motivation for defining the pasture production functions for P was to develop a more objective basis for offering fertiliser P advice to farmers, and in particular to develop the technology to offer fertiliser advice based on economic outcomes. This has not been possible previously (Edmeades 1995). This is important for economic and environmental reasons—farming above the economic optimal nutrient level (the level required for long-term profitability) is uneconomic and increases the environmental risk of P runoff. Equally, farming below the economic optimal may not be in the farmer's or society's financial and social interests. To develop an econometric P model, based on the response functions, first required dealing with some other technical issues.

Relevance of mowing trials?

The pasture production in most of the trials (98%) used to generate these New Zealand production functions, was measured in what are typically called "mowing trials" in which animals are excluded and a large proportion of the harvested pasture (the clippings) are returned to their respective plots, to simulate the return of animal excreta (see Lynch (1966) for a discussion of the various techniques). The question frequently arises: how relevant are these results to the normal field situation where pastures are grazed *in situ*? The major confounding factors are selective grazing, pasture treading, and uneven return of animal excreta.

Morton et al. (1995) have summarised all the relevant New Zealand research comparing the effects of applied P on pasture production, measured in mowing trials (no animal influence with return of clippings) and in grazing trials (animal influence and normal return of animal excreta). They subsequently reported the results of a further study (Morton & Roberts 2001). They concluded that, while the absolute pasture production measured in mowing trials was less than that recorded under grazing trials, the relative responses to applied P were similar. They concluded, therefore, that the results from mowing trials are a valid estimate of relative response to applied P. This is essentially the same conclusion reached by earlier researchers in New Zealand (Lynch 1947; Elliot & Lynch 1958). Cayley & Hannah (1995) measured pasture responses to applied P fertiliser under a grazing influence and compared these to the responses measured under three mowing regimes (low, medium, and high mowing frequency). Results derived from their paper are shown in Fig. 8, and indicate that the relative pasture response to P under grazing is similar to that measured under mowing at the most frequent defoliation, averaging the data over 4 years. Similar to the New Zealand results, the absolute pasture production was greater under the "grazing" regime. These results also indicate that there is an interaction between relative pasture production and the frequency of defoliation, suggesting that care is required when setting up mowing trial protocols.

It is concluded, based on the results discussed above, that relative pasture production can be predicted, with reasonable accuracy, from knowledge of the soil group and the Olsen P level, and that the predicted relative yield is a realistic measure of what is a likely relative increase in pasture production under normal grazing.

Several trials in New Zealand and Australia (Morton et al. 1995; Cayley et al. 1998, 1999; Morton et al. 2003) have measured the effect of P fertiliser on both pasture and animal production. Morton et al. (1995) concluded, based on three trials under sheep and one under dairying, that relative P responses in animal production (e.g., sheep and lamb liveweights and fleece weights and milk solids production) were typically less than relative responses in pasture production. However, such a conclusion must be qualified in terms of which animal production parameter is measured (Morton et al. 1995; Cayley et al. 1998, 1999) and the stocking rate, or

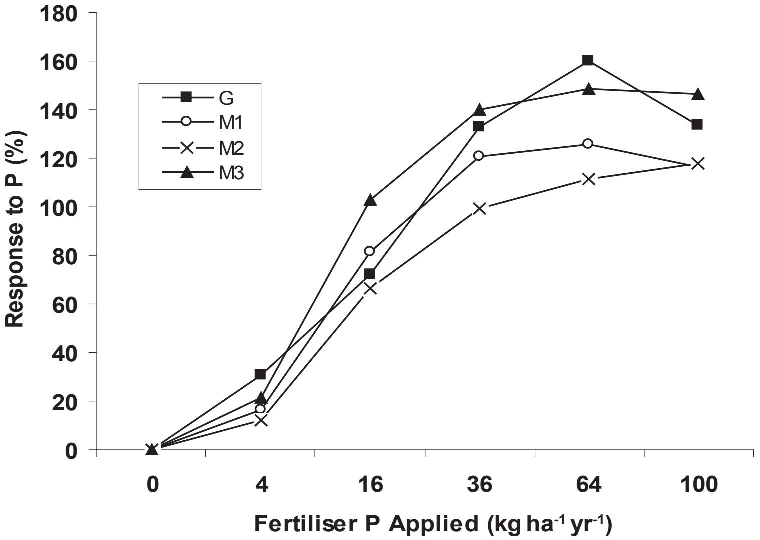


Fig. 8 The relationship between relative pasture production and fertiliser phosphorus applied as measured under a grazing influence (G) and three levels of defoliation frequency under mowing (M1, M2, and M3) (from Cayley & Hannah 1995).

more specifically the grazing pressure, at which the measurements are made (Carter & Day 1970; Cayley et al. 1998, 1999).

Based on the above it is concluded that relative pasture production can be used as the major determinant for animal production, noting the qualifications discussed above.

Economic assessment

Metherell et al. (1995) have discussed elsewhere the approach adopted and the algorithms used to determine the economic outcomes from different fertiliser input strategies at a farm specific level, based on the P response functions. Only several points need to be commented on in the context of this review. First, the Olsen P pasture production functions are based on the relative yields and not absolute yields. This decision was made in part to normalise the data and hence include more trial data, but, more importantly, it overcame the problems previously experienced in New Zealand with the practical application of the steady-state Cornforth and Sinclair P model (Cornforth & Sinclair 1982) for making fertiliser recommendations: namely the need to estimate, and the difficulty of estimating, the absolute maximum production and the actual pasture utilisation at a given site. The decision to normalise the data, in turn, gave rise to the problem of predicting likely increases in animal production, and hence the economic benefits, from increases in relative pasture production, given the many interacting factors discussed earlier. This problem was circumvented (Metherell et al. 1995) by using the farm, or the block within a farm, gross margin (gross margin = total income minus the variable costs) as a measure of the economic efficiency of the farm. In effect, the farm gross margin integrates into one figure the efficiency of converting pasture into a dollar value at a farm specific level. This includes such factors as stocking rate, pasture utilisation, the variable costs of production and the dollar value of the product. Thus, for calculation purposes the gross margin is increased in proportion to the increase in relative pasture production, assuming all other factors are equal.

Finally, the accuracy of the model when applied to specific farm situations requires comment. The model, as developed, is based on the relationship between the average annual relative production and soil Olsen P. It follows that any advice offered, in terms of fertiliser requirements, assumes an average year in terms of growth conditions. In the absence of a reliable method to predict climatic conditions this is a necessary compromise. This means, however, that fertiliser inputs, and their economic implications, could be over- or underestimated relative to a specific season, to the extent (frequency and amplitude) that year-to-year variations in pasture production occur. This problem is minimised by taking a long-term perspective and it is for this reason that the econometric model has a 10- to 15-year planning horizon.

The econometric model does require a number of farm (or block) specific inputs: physical data (soil group, topography), financial information (gross margin, stock costs and value), fertiliser costs (including transport and spreading) and soil fertility (Olsen P), and the accuracy of the model output is, of course, dependant on the accuracy of the inputs. Of these inputs the Olsen P level is usually the least accurate. To minimise this problem it is becoming commonplace for New Zealand farmers to establish soil sampling protocols which required soil tests to be taken from the same transects, at the same time of the year, on an annual basis. In this manner the trends in the Olsen P levels can be monitored over time and a more precise measure of the Olsen level on a farm (or a given block of the farm) can be established.

CONCLUSIONS

Defining the relationships—the production functions—between soil P (Olsen P) and relative pasture production for the major soil groups in New Zealand has been successful by the application of Bayesian statistics to a large database of P field trials. This was particularly so where there was a large number of field trials in a given dataset. In such cases reasonably precise estimates of relative pasture production at a given Olsen P level were possible. There was good agreement, allowing for experimental error, between the empirically derived production functions and those predicted by a dynamic P model. For some soil groups (the volcanic soils and podzols) there were irregularities in the production functions due to the intrusion of uncontrolled variability. More trials on these soils are required to refine these relationships. Organic soils (peats) were not represented in the database but subsequent research suggests that these soils have similar production functions to the pumice soils.

Critical Olsen P levels (Olsen P required to achieve 97% relative yield) ranged from 12 to 50 depending on soil group. The results indicated that they were related to ASC and/or soil volume weight. More research is required to test these possibilities.

There was reasonable agreement between estimates of soil P buffering capacity as measured in the field and those derived from a model, which showed that ΔP decreases with increasing Olsen P. It is concluded that the P model may not be measuring all the site specific factors measured in the field. In the case of the podzols the model systematically overestimated the field ΔP.

There was a weak positive relationship between ΔP and ASC, after leaving out the results from one soil group (sands). It is suggested that the reason for this poor relationship is that the laboratory determined buffer capacity (ASC) does not account for all the necessary soil P processes which occur in the field. Nevertheless, ASC is still a useful diagnostic tool for assisting in differentiating between soil groups and hence defining the appropriate production function to apply in any given situation.

The results suggest that there are factors other than those based on soil chemical properties which may impact on and define the relationship between relative pasture production and soil P. These can be assigned to two categories: those factors which affect the ability of the soil to supply P for plant uptake, and those that affect the ability of the plant to acquire soil P. It is concluded that further progress towards improving our ability to predict pasture responses to fertiliser P will depend on quantifying the latter effects.

It is concluded that the relative responses to P in mowing trials are an appropriate method to quantify pasture responses to P under grazing, and that such estimates are a reliable predictor of likely increases in animal production. It is concluded, therefore, that the econometric P model developed for New Zealand pastoral situations, based on these results, is a reliable method for assessing the likely agronomic, financial, and investment effects of any given fertiliser strategy on a given farm. This was not previously possible but is essential for the sustainable use of P fertilisers in pastoral farming.

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REFERENCES

Burkitt LL, Moody PW, Gourley CJP, Hannah MC 2002: A single phosphorus buffering index for Australian soils. Australian Journal of Soil Research 40: 497–513.

Carter ED, Day HR 1970. Interrelationships of stocking rate and superphosphate rate on pasture as determinants of animal production. Australian Journal of Agricultural Research 21: 473–491.

Cayley JWD, Hannah MC 1995. Response to phosphorus fertiliser compared under grazing and mowing. Australian Journal of Agricultural Research 46: 1601–1619.

Cayley JWD, Hannah MC, Kearney GA, Clark SG 1998. Effects of phosphorus fertiliser and rate of stocking on the seasonal pasture production of perennial ryegrass-subterranean clover pasture. Australian Journal of Agricultural Research 49: 233–248.

Cayley JWD, Kearney GA, Saul GR, Lescun CL 1999. The long-term influence of superphosphate stocking rate on the production of spring-lambing Merino sheep in a high rainfall zone in southern Australia. Australian Journal of Agricultural Research 50: 1179–1190.

Colwell JD 1963. The estimation of phosphorus fertiliser requirements of wheat in southern New South Wales by soil analysis. Australian Journal of Experimental Agriculture and Animal Husbandry 3: 190–197.

Cornforth IS, Sinclair G 1982. Fertiliser recommendations for pasture and crops in New Zealand. Wellington, New Zealand, Ministry of Agriculture and Fisheries.

Edmeades DC 1995. Modeling nutrient requirements—AgResearch's approach. In: Currie LD, Loganathan P ed. Fertiliser requirements of grazed pastures and field crops. Proceedings of a workshop. Occasional Report No. 8. Massey University, Palmerston North, New Zealand. Pp. 9–11.

Edmeades DC, Cornforth IS, Wheeler DM 1988. Soil: testing, getting maximum benefit. Wellington, New Zealand, Ministry of Agriculture and Fisheries, Primedia.

Edmeades DC, Roberts AHC, O'Connor MB, Morton JD 2003. Soil testing: a modern Prometheus. In: Currie LD, Hanly JA ed. Tools for nutrient and pollutant management. Proceedings of a workshop. Occasional Report No. 17. Massey University, Palmerston North, New Zealand. Pp. 42–50.

Edmeades DC, Thorrold BS, Roberts AHC 2005. The diagnosis and correction of sulfur deficiency and the management of sulfur requirements in New Zealand pastures: a review. Australian Journal of Experimental Agriculture 45: 1205–1223.

Elliot IL, Lynch PB 1958. Techniques of measuring pasture production in fertiliser trials. New Zealand Journal of Agricultural Research 1: 498–521.

Feyter C 1993. Establishment of P, K and S databases. Internal report. Hamilton, New Zealand, AgResearch.

Fleming NK, Bolland MDA, Gilbert MA 1997. Effect of reactive phosphate rocks and water-soluble phosphorus fertilisers on extractable phosphorus concentrations in soil. Australian Journal of Experimental Agriculture 37: 1009–1017.

GenStat 2005. Version 8.1.0.156. 8th ed. Oxford, VSN International Ltd.

Grigg JL 1968. Prediction of plant responses to fertilisers by means of soil tests II. Correlations between soil phosphate tests and phosphate responses of ryegrass grown in pot experiments on Recent, Gley Recent, and Gley soils. New Zealand Journal of Agricultural Research 11: 345–358.

Grigg JL 1972. Prediction of plant responses to fertilisers by means of soil tests III. The relationship between levels of soil phosphorus and responses to applied phosphorus in pasture topdressing trials. New Zealand Journal of Agricultural Research 15: 643–652.

Grigg JL 1977. Prediction of plant responses to fertilisers by means of soil tests versus soil tests for phosphorus availability in brown-grey and dry subhydrous yellow-grey earths. New Zealand Journal of Agricultural Research 20: 315–326.

Helyar KR, Spencer K 1977. Sodium bicarbonate soil test values and the phosphate buffering capacity of soils. Australian Journal of Soil Research 15: 263–273.

Holford ICR 1997. Soil phosphorus: its measurement and its uptake by plants. Australian Journal of Soil Research 35: 227–239.

Lynch PB 1947. Method of measuring the production of grasslands. New Zealand Journal of Science and Technology 28A: 385–405.

Lynch PB 1966. Conduct of field experiments. Bulletin 399. New Zealand Department of Agriculture.

McCall DG, Thorrold BS 1991. Fertiliser history is a useful predictor of soil fertility status. Proceedings of the New Zealand Grassland Association 53: 191–196.

Metherell AK 1994. A model for phosphate fertiliser requirements for pastures—incorporating dynamics and economics. In: Currie LD, Loganathan P ed. The efficient use of fertilisers in a changing environment: reconciling productivity and sustainability. Proceedings of a workshop. Occasional Report No. 7. Massey University, Palmerston North, New Zealand. Pp. 18–37.

Metherell AK, McCall DG, Woodward SJR 1995. Outlook™: a phosphorus fertiliser decision support model for grazed pastures. In: Currie LD, Loganathan P ed. Fertiliser requirements of grazed pastures and field crops. Proceedings of a workshop. Occasional Report No. 8. Massey University, Palmerston North, New Zealand. Pp. 24–39.

Morton JD, Roberts AHC 1999. Fertiliser use on New Zealand sheep and beef farms. Auckland, New Zealand, New Zealand Fertiliser Manufacturer's Research Association. 40 p.

Morton JD, Roberts AHC 2001. Pasture responses to soil phosphorus levels measured under mowing and dairy grazing. New Zealand Journal of Agricultural Research 44: 259–268.

Morton JD, Waller JD, Ledgard SF, Roberts AHC 1995. Effect of measurement technique on responses to phosphorus fertiliser. In: Currie LD, Loganathan P ed. Fertiliser requirements of grazed pastures and field crops. Proceedings of a workshop. Occasional Report No. 8. Massey University, Palmerston North, New Zealand. Pp. 12–20.

Morton JD, Smith LC, Metherell AK 1999. Pasture yield responses to phosphorus, sulphur and potassium applications on North Otago soils, New Zealand. New Zealand Journal of Agricultural Research 42: 133–146.

Morton JD, McDowell RW, Monaghan RM, Roberts AHC 2003. Balancing phosphorus requirements for milk production and water quality. Proceedings of the New Zealand Grassland Association 65: 111–116.

O'Connor MB, Gray MH 1984. Fertiliser requirements of Gisborne-East Coast hill country. Proceedings of the New Zealand Grassland Association 45: 83–91.

O'Connor MB, Longhurst RD, Johnston TJM, Portegys FN 2001. Fertiliser requirements for peat soils in the Waikato region. Proceedings of the New Zealand Grassland Association 63: 47–51.

Olsen SR, Cole CV, Watanabe FS, Dean LA 1954. Estimation of available phosphorus in soils by extraction with sodium carbonate. Circular 939. United States Department of Agriculture. 19 p.

Rajendram G, Perrott K, Waller J, Kear M, Dewar D 2003. The Olsen test: should it be on a volume of weight basis? In: Currie LD, Hanly JA ed. Tools for nutrient and pollutant management. Proceedings of a workshop. Occasional Report No. 17. Massey University, Palmerston North, New Zealand. Pp. 271–277.

Roberts AHC 1987. Seasonal variation in soil test and nutrient content of pastures at two sites in Taranaki. New Zealand Journal of Experimental Agriculture 5: 283–294.

Roberts AHC, Morton JD 1999. Fertiliser use on New Zealand dairy farms. Auckland, New Zealand, New Zealand Fertiliser Manufacturer's Research Association. 36 p.

Roberts AHC, Morton JD, Metherell AK 1995. Comparison of 'Outlook' model predictions with the trends in Olsen P measured on farms. In: Currie LD, Loganathan P ed. Fertiliser requirements of grazed pastures and field crops. Proceedings of a workshop. Occasional Report No. 8. Massey University, Palmerston North, New Zealand. Pp. 54–79.

Saunders WMH 1968. Phosphorus. In: Soils of New Zealand, Part 2. New Zealand Soil Bureau, Bulletin 26(2).

Saunders WMH, Sherrell CG, Gravett IM 1987. A new approach to the interpretation of soil tests for phosphate response by grazed pasture. New Zealand Journal of Agricultural Research 30: 67–77.

Sherrell CG 1970. Comparison of chemical extraction method for the determination of "available" phosphate in soils. I. Correlations between methods and yield and phosphorus uptake by white clover grown on 16 North Island soils in the glasshouse. New Zealand Journal of Agricultural Research 40: 559–567.

Sinclair AG, Johnston PD, Smith LC, Roberts AHC, O'Connor MB, Morton JD 1997. Relationship between pasture dry matter yield and soil Olsen P from a series of long-term field trials. New Zealand Journal of Agricultural Research 40: 559–567.

Symth JH, Dumanski J 1994. Progress towards an international framework for evaluating sustainable land management (FESLM). Transactions of the 15th World Congress of Soil Science, Accapulco, Mexico, July 1994 Volume 6a.

Truog E 1930. The determination of readily available phosphorus in soils. Journal of American Society of Agronomy 22: 874–882.

Upsdell MP 1994. Bayesian smoothers as an extension of non-linear regression. The New Zealand Statistician 29: 66–81.