Phosphate rock fertilisers to enhance soil P status and P nutrition on organic cropping farms.

A thesis presented in partial fulfilment of the

requirements for the degree of

Master of Plant Science

at Massey University

Scott Robert Shaw

2009

Massey University

College of Sciences

Institute of Natural Resources
Agronomy
Private Bag 11 222
Palmerston North,
New Zealand
Telephone: 64 6 356 9099
Facsimile: 64 6 350 5632

CERTIFICATE OF REGULATORY COMPLIANCE

This is to certify that the research carried out in the Masterate Thesis entitled Phosphate rock fertilisers to enhance soil P status and P nutrition on organic cropping farms, in the Institute of Natural Resources (Agronomy) at Massey University, New Zealand:

(a) is the original work of the candidate, except as indicated by appropriate attribution in the text and/or in the acknowledgements;

(b) that the text, excluding appendices/annexes, does not exceed 40,000 words;

(c) all the ethical requirements applicable to this study have been complied with as

required by Massey University, other organisations and/or committees (The New Zealand Institute for Plant and Food Research Ltd) which had a particular association with this study, and relevant legislation.

Candidate's Name: Scott Robert Shaw

Signature:

Date:

Supervisor's Name: Dr. James Millner

Signature:

Date:

Co-Supervisor's Name: Dr. Stephen Trolove

Signature:

Date:

ABSTRACT

The soils used by the East Coast Organic Producers Trust (ECOPT; the grower group that this study is targeted towards) have exceptionally low soil Olsen P concentrations (ca. 6 mg/L). These and other limitations (e.g. poor weed and pest and disease control) result in many ECOPT growers being unable to produce economic yields on anything other than small scale gardens. Fertilisers and manures are seldom used by these growers, which exacerbates the problem. Thus, the object of this research was to provide information to ECOPT on which fertilisers and application strategies would provide the best returns on their phosphorus (P) fertiliser investment.

The experimental work was carried out in two parts. A laboratory study tested a range of phosphate rock (PR) based fertilisers and application rates; Ben Guerir reactive phosphate rock (RPR; 67, 133, 267, 533 and 1,333 mg P/kg soil), BioPhos and BioSuper (267 and 1,333 mg P/kg soil) and a no fertiliser Control. Soil fertiliser mixtures were incubated for 155 days and periodic measurements of PR dissolution, soil pH and Bic-P (analogous to Olsen P but expressed in µg/g) were undertaken. The field study used fewer application rates and two application methods; banded and broadcast. Broadcast plots were applied at 678 mg P/kg soil (488 kg P/ha); banded RPR was applied at 236, 678 and 1475 mg P/kg soil (40, 115 and 250 kg P/ha respectively) and banded BioPhos and BioSuper at 678 mg P/kg soil (115 kg P/ha). A Control was also included. Fertilisers were applied in October 2004 and changes in soil pH and Bic-P were measured in the broadcast plots only over a 344 day period. Potato (*Solanum tuberosum* L. cv. Desiree) was the test crop.

Regression analysis was used to generate exponential equations to describe the changes in Bic-P over time (ΔBic-P). Differences between fertilisers in the amount of P dissolved and pH fluxes were used to explain the differences in ΔBic-P. BioSuper dissolved quicker and generated greater ΔBic-P than RPR and BioPhos, which were similar. Higher application rates produced greater increases in Bic-P than lower rates but decreased the % of P applied that dissolved. The increase in Bic-P over time from

fertiliser application was much slower in the field compared with the laboratory. This was put down to differences in experimental conditions; mainly soil pH and soil aggregate surface area.

Potato tuber yield (mean = 35 t/ha) did not respond to any of the fertiliser treatments despite a significant increase in P concentration of the shoots mid-way through the season in all broadcast treatments (shoot P concentration was not analysed in the banded plots). Water and N availability were the main limiting factors in this season as the crop was not irrigated and soil N supply was insufficient to produce a full canopy.

Phosphorus response curves generated using the fertiliser response model PARJIB (Reid, 2002), and an economic analysis, indicated that for RPR and BioPhos the optimum economic application rate was 200 kg P/ha and for BioSuper it was 100 kg P/ha (applied every third and second year respectively).

ACKNOWLEDGEMENTS

I am extremely grateful for, and would like to acknowledge the commitment, guidance and support of my supervisors Dr Stephen Trolove and Dr James Millner throughout this research project. Thank you both!

Thanks also to Dr Huub Kerckhoffs, without your support this research would not have been possible. I would also like to acknowledge one of my greatest mentors Dr Peter Stone. And Dr Jeff Reid and Robert Zykowski for your time spent assisting with the crop-model simulations. Also, Isabel Sorensen for your help in the laboratory.

Special thanks go to Moana Puha for your technical input and enthusiasm on our long and sometimes extended trips away to the East Coast, and to your parents John and Violet Puha for their hospitality when we stayed with them. Thank you also Wallace and Roberta Atkins for hosting the field experiment. I learnt a lot from you both and was truly humbled by your commitment, patience and perseverance. You are great leaders for the region and your lead-by-example style is exactly what the region needs more of. Keep up the great work!

Finally, thanks to all the wonderful people I met on "the Coast" during the time I spent there. I look forward to meeting each of you again in future.

This research was funded by the Foundation for Science Research and Technology (FRST), under the research program - Science for Community Change (contract C02X0305).

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Description
Al	Aluminium
ANOVA	Analysis of variance
ARL	Analytical Research Laboratories
$BaCl_2$-TEA	Barium chloride-Trienthanolamine
Bic-P	Bicarbonate (pH 8.5) soluble phosphorus (analogous to Olsen P except is expressed as w/w)
BioP	BioPhos (ex. Sieber Technologies Ltd)
BioP1	BioPhos applied at 67 mg P/kg soil
BioP2	BioPhos applied at 133 mg P/kg soil
BioP3	BioPhos applied at 267 mg P/kg soil
BioP4	BioPhos applied at 533 mg P/kg soil
BioP5	BioPhos applied at 1333 mg P/kg soil
BioS	BioSuper; a 5:1 blend of Ben Guerir RPR and S^o (ex. Ravensdown Ltd)
BioS1	BioSuper applied at 67 mg P/kg soil
BioS2	BioSuper applied at 133 mg P/kg soil
BioS3	BioSuper applied at 267 mg P/kg soil
BioS4	BioSuper applied at 533 mg P/kg soil
BioS5	BioSuper applied at 1333 mg P/kg soil
C	Carbon
Ca	Calcium
ca.	Circa
$CaCO_3$	Calcium carbonate
CEC	Cation exchange capacity
cf.	Compare
CI	Confidence interval
DAFA	Days after fertiliser application
DM	Dry matter
ECOPT	East Coast Organic Producers Trust
e.g.	Example
F^-	Fluoride ion
Fe	Iron
FRST	Foundation for Research Science and Technology
FW	Fresh weight
FRI	Fraction of radiation intercepted
GAI	Green leaf area index (m^2/m^2)
GDD	Growing degree days
ha	Hectare
H_2PO_4	Phosphoric acid
HCO_3^-	Bicarbonate ion
i.e.	Specifically
ICP-OES	Inductively coupled plasma-optical emission spectrometry
K	Potassium
KCl	Potassium chloride
LAI	Leaf area index (m^2/m^2)
$LSD_{0.05}$	Least significant difference at the 5 % probability level
MC	Moisture content
Mg	Magnesium
N	Nitrogen
n	Number
Na	Sodium
NAC	Neutral ammonium citrate
$NaHCO_3$	Sodium bicarbonate
NH_4^+	Ammonium ion
NO_3^-	Nitrate ion
OH-	Hydroxide ion
P	Phosphorus
P_i	Inorganic phosphorus
PR	Phosphate rock
P_{sat}	P-saturation of the soil (mg P/m2 soil)
P_{yld}	Potential yield
ROI	Return on investment

Abbreviation	Description
RPR	Reactive phosphate rock
RPR1	Ben Guerir RPR applied at 67 mg P/kg soil
RPR2	Ben Guerir RPR applied at 133 mg P/kg soil
RPR3	Ben Guerir RPR applied at 267 mg P/kg soil
RPR4	Ben Guerir RPR applied at 533 mg P/kg soil
RPR5	Ben Guerir RPR applied at 1333 mg P/kg soil
S	Sulphur
S^o	Elemental sulphur
SA	Specific surface area
SD	Sample date
SF	Scaling factor
SEM	Standard error of the mean
SFP	Soil fertiliser P (concentration)
spp.	Species
SR	Solar radiation
SWD	Soil water deficit
TSP	Triple superphosphate
viz.	Visibly
X_B^{95}	DAFA for 95 % of model asymptote (-B)
SFP	Soil fertiliser-P concentration (mg P/kg or l of soil)
ΔBic-P	Change in Bic-P
ΔCa	Change in Calcium

CHAPTER 1

1 INTRODUCTION

1.1 PRODUCTION LIMITATIONS OF THE EAST COAST ORGANIC PRODUCERS TRUST

The East Coast Organic Producers Trust (ECOPT) is a non-profit collective of Maori organic-vegetable growers, whose aim is to provide support and market channels for organic producers on the East Coast (Figure 1.1). In the year 2000 there were over 50 ECOPT members, but since then this number has decreased considerably for various reasons (Puha et al., 2005).

Enterprises of the ECOPT range from mixed cropping and livestock, to intensive production of a range of vegetable crops including potato (*Solanum tuberosum* L.*)*, kumara (*Ipomoea batatas* L.*)*, sweet corn (*Zea mays* L.) etc, with a small number (and area) of horticultural fruit crops. There are large differences among growers in the resources available and the skills and knowledge that are required to sustain a successful crop production enterprise. There are also a large number of limitations to production including poor weed control, poor soil fertility, lack of irrigation, poor drainage and soil quality/structure, and poor pest and disease management (Puha et al., 2005).

The majority of ECOPT growers use no (or minimal) external inputs, i.e. these growers simply cultivate the soil and grow their crops with the only significant management input being hand and/or mechanical weeding. An example of the type of outcome that can be expected from this type of approach was evidenced in 2003 at Waipiro Bay when about 5 ha of (ECOPT) land was cultivated and planted with potatoes, and only a small corner (ca. 0.5 ha) of the paddock produced an “economic” crop. The main reasons for this were a combination of poor soil fertility and disease (late blight; *Phytophthora infestans* M.). Soil tests taken after the paddock was planted indicated soil Olsen P was 6 mg/L with Ca comprising only 20.5 % of base saturation, both well

below recommended ranges (Prasad et al., 1988; Goldspink and Howes, 2000). Had soil tests been taken before the paddock was planted, these would have highlighted the low nutrient status of the soil and the grower(s) advised to increase the P and Ca fertility before planting. But this was not done. Control options for late blight in potatoes include regular sprays of copper/Bordeaux mixture and/or compost-tea[1]; and these were also not applied. There are many other examples of very low yielding crops from ECOPT growers' paddocks with yields often only 10 % those which could be expected using conventional production methods (e.g. synthetic fertilisers, herbicides and pesticides).

On the other hand, one or two growers are extremely proactive; following prescriptive soil fertility management and crop rotation systems that help mitigate nutrient deficiencies and as well as weed, pest and disease pressure. None of the ECOPT growers have access to large-scale irrigation equipment or the necessary water supply and resource consent required to irrigate.

A soil fertility survey conducted prior to the onset of this study, covering 14 ECOPT paddocks indicated that soil Olsen P, and often Ca and K levels were insufficient for the production of high yielding crops (Table 1.1). To alleviate nutrient deficiencies ECOPT growers need to implement a nutrient management plan specifically designed for each paddock. Such a plan may include fertilisers and/or composts, and carefully chosen crop rotations including legumes and/or ley periods to maintain sufficient N fertility for subsequent crops.

[1] A dilute liquid extract from compost containing beneficial micro-organisms.

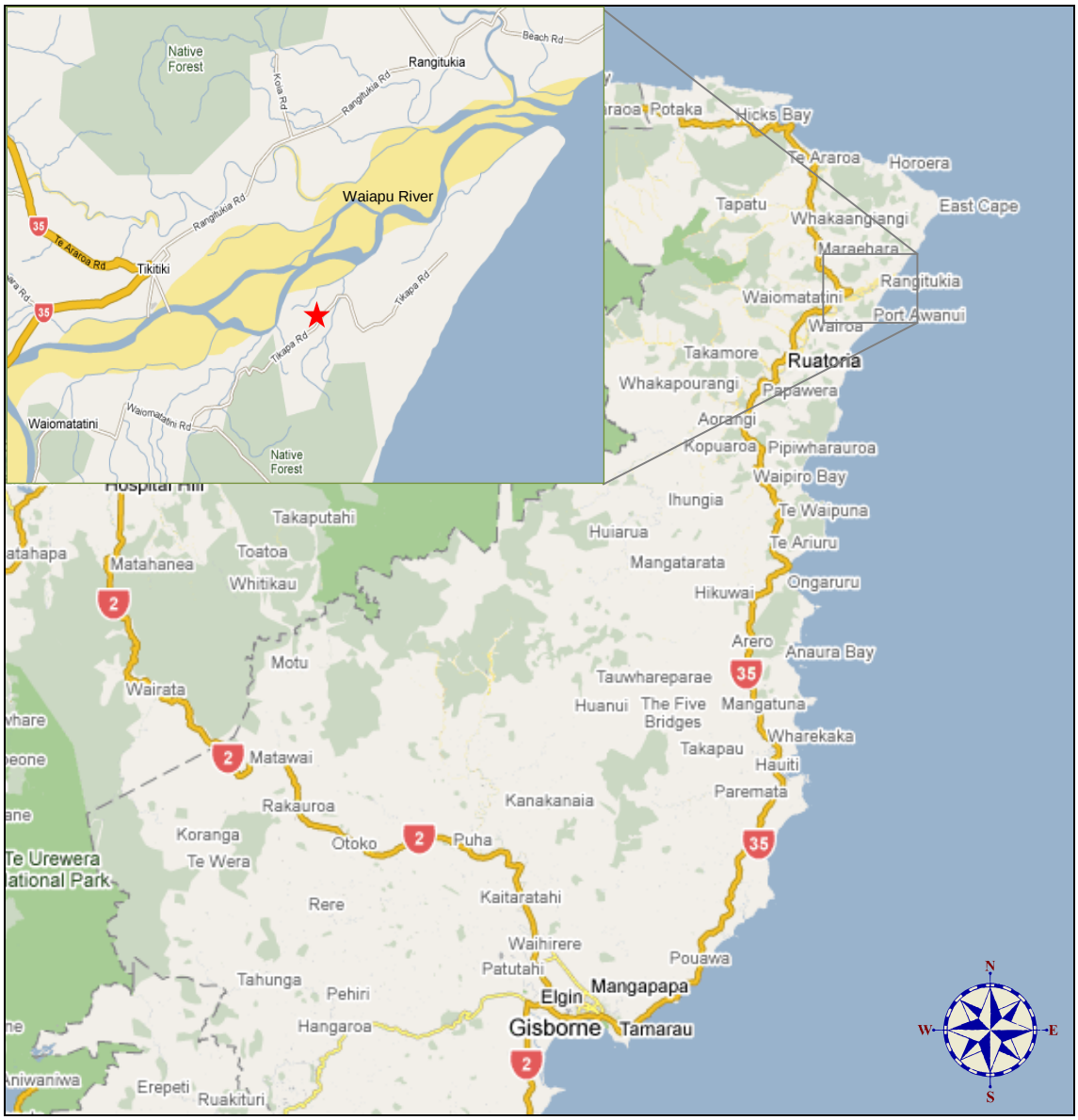


Figure 1.1. Eastland district, New Zealand. Inset is the location of the field experiment, depicted by the star (Tikapa Rd). Members of the East Coast Organic Producers Trust range from Waipiro Bay in the south to Hicks Bay in the north. Map courtesy of Google Maps (http://maps.google.co.nz/maps).

Table 1.1. Selected soil chemical properties of 14 paddocks of the East Coast Organic Producers Trust. Optimum range data (for vegetables) sourced from Clarke et al. (1986).

	pH	Olsen- P MAF	Calcium MAF	Magnesium MAF	Potassium MAF	Sodium MAF	CEC me/100 g
Mean	5.7	6	3	26	5	6.4	11.1
SEM	0.6	0.6	0.9	6	0.7	0.78	1.44
Optimum range	5.5-6.0	35-65	8-15	20-30	12-20	1-10	-

In essence, many of the ECOPT growers face a difficult challenge trying to grow crops organically on a commercial scale. Unfortunately there is no quick-fix available to these growers. The best way to increase production is an integrated, proactive approach to crop management; including nutrition, and weed, pest and disease control. Once these issues are adequately managed irrigation may be used to elevate production even further. Bearing in mind that applying irrigation will increase weed pressure and in some instances may also enhance pest and disease pressure.

This study was part of a large (5-year) government funded research program called Science for Community Change (FRST contract C02X0305), and was aimed at providing answers to the most common production limitation faced by ECOPT growers; low P fertility. This was because P fertility was lower than optimal in every ECOPT paddock tested prior to the onset of this study; other nutrients were low in some paddocks but not others. By enhancing P fertility, ECOPT growers will overcome one of the major nutritional production barriers. Other limitations to production were addressed though other studies and workshops dealing with specific issues, including site selection, nutrient management, crop establishment, weed and pest and disease control, and marketing. The aim of these studies/workshops was to develop an integrated production system from which ECOPT growers could enhance both the yield and quality of their crops, and were not included in this study or this document. For more detail on these workshops etc see Te Pànui (www.panui.org.nz).

1.2 PROBLEM BACKGROUND

Phosphorus (P) is one of the most common plant nutrients limiting production in agricultural soils (Russell, 1988), and the soils used by the ECOPT are no exception to this (Table 1.1). Organic principles (and regulations) state that organic producers cannot apply synthetic chemicals (including fertilisers) to their land or produce (BioGro, 2008). Moreover, P is often limiting on organic farms (Nguyen et al., 1995; Evans et al., 2006). A major contributor to this is that organic growers can only apply naturally occurring fertilisers/manures, such as PR. Phosphate rocks increase plant-available P concentrations at a slower rate and a lot less per unit of P applied than synthetic

water-soluble inorganic phosphate (P_i) fertilisers such as superphosphate (SP). Thus organic growers do not usually get an immediate plant growth response, unlike conventional growers who apply water-soluble P_i fertilisers.

Well-managed organic farms tend to apply maintenance applications of P fertilisers/manures, however some (less well-managed) farms run at a negative P balance, where P outputs exceed P inputs (Evans et al., 2006). These later farms are by definition unsustainable (Smyth and Dumanski, 1995) and ECOPT farms generally fall into this category.

As mentioned above, many of the ECOPT growers have been struggling to produce high yielding crops on anything other than small-scale (home) gardens, and one of the major barriers to production is the low plant-available P concentrations of their soils. The average Olsen P concentration of the ECOPT growers' soils was very low; around 6.0 $^{+}/_{-}$ 0.6 mg/L (Table 1.1). Most crops require Olsen P concentrations much higher than this for optimal yields (Clarke et al., 1986; Prasad et al., 1988). Calcium and K concentrations were also lower than optimal in many paddocks (but not all).

To increase the plant-available P concentration of their soils ECOPT growers need cost-effective, accessible forms of organic-certified P fertiliser. Ben Guerir RPR (ex Ravensdown Ltd) and BioPhos (ex Ballance Agrinutrients Ltd) are two such products on the market. Another option is to apply elemental sulphur (S^o) in conjunction with PR (typically in a 1:5 blend respectively; commonly referred to as BioSuper) which enhances the agronomic effectiveness of the PR by accelerating PR dissolution (see section 2.3.2). Phosphate rock fertilisers contain significant amounts of Ca (ca. 33 %), which may also help address the low Ca fertility of some ECOPT soils.

Although there has been a large quantity of research done on direct application of PR to agricultural soils, most of this has been done on dry-stock farms where fertiliser applications are topical (i.e. applied to the surface of the soil). Relatively little work has been done on cropping farms where fertilisers are incorporated into the soil, and which is often irrigated. Incorporation enhances PR dissolution (Kanabo and Gilkes,

1988a) and may affect the optimal and/or threshold conditions required for dissolution to occur. There has also been no published work on Ben Guerir RPR and only one piece of published work on BioPhos. This indicates that the agronomic effectiveness of these products warrants investigation.

1.3 OBJECTIVES

This research is aimed at investigating the relative agronomic effectiveness of three organic-certified PR-based fertilisers (Ben Guerir RPR, BioPhos and BioSuper) on the alluvial soils used by the ECOPT. Determination of the optimum economic application rate of each fertiliser was a key goal, considered vitally important in the development of an integrated production system aimed at helping enhance crop yields and quality of the ECOPT growers.

CHAPTER 2

2 LITERATURE REVIEW

2.1 PHOSPHORUS NUTRITION

2.1.1 PHOSPHORUS NUTRITION IN ORGANIC AGRICULTURE

Global markets are now demanding evidence that food is produced sustainably (GlobalGAP)[2]. Therefore it is vitally important that organic cropping farms use scientifically validated and documented sustainable nutrient management plans for key external nutrient inputs (including P). There are currently no such nutrient management plans for P nutrition of organic cropping farms documented in the literature. With current technology PR is the most cost effective and readily available form of P for organic production systems.

The only published research done in New Zealand investigating crop (P) nutrition on organic farms indicated that P nutrition on two out of the three organic farms studied was not sustainable (Nguyen et al., 1995). In Nguyen et al. (1995), one farm had a 54 kg P/ha/year deficit; and another a 33 kg P/ha/year deficit. Estimated P release from the labile pool was about 3 kg P/ha/year for both of these farms and it was concluded that large applications of P fertilisers/manures will be required in the future to sustain current production levels on these farm.

Prior to the development of synthetic fertilisers farmers relied on a combination of fallow/ley periods, composts, manures, legumes and crop rotations to manage soil fertility. These practices are now the key underlying principles of organic agriculture (Watson et al., 2002).

[2] A private, Global Agricultural Production standards accreditation organisation; www.globalgap.org. See references list for more detail.

Nitrogen fixation is the most important N source in organic farming. Insufficient P supply to legumes may reduce their N-fixation capacity and total yield. Romer and Lehne (2004) showed that when PR was applied there was a significant improvement in the P content of red clover (*Trifolium pratense* L.) and oats (*Avena sativa* L.*)* and an increase in the N content and dry matter (DM) yield of red clover, the later the result of enhanced N-fixation. Thus, by increasing the P status of their soils organic growers could not only expect yield responses resulting from enhanced P availability, but if legumes are grown in the rotations (e.g. over winter as green manures), N nutrition of these and succeeding crops may also be enhanced.

Some plant species are better able to utilise and/or enhance the rate of P released from PR (e.g. legumes and rape [*Brassica napus* L.]), so organic growers might benefit using these types of crops, particularly in the first few years following capital applications of PR fertilisers. The efficiency of potatoes to utilise P from PR has not been published. This, combined with the fact that potatoes are an important crop for the ECOPT growers and a known P responsive crop (Prasad et al., 1988), made potatoes an ideal test crop for the present study.

2.1.2 PLANT RESPONSE TO PHOSPHATE ROCK FERTILISERS

There is much literature detailing optimal and/or critical plant-available soil P concentrations for most commonly grown arable/vegetable crops (Clarke et al., 1986; Prasad et al., 1988). Unfortunately the wide range of tests used to estimate P availability to plants can make comparisons between studies difficult. Although in some circumstances Olsen P may not be the best predictor of plant-available P where PR has been used (Saggar et al., 1992; Saggar et al., 1999), Olsen/Bic-P is the primary focus here because i) it is the test most commonly used in New Zealand ii) it is the test used in the experimental work of the present study and iii) the present study is aimed at investigating the effects of PR fertiliser applied in one dose (capital application) at the start of the experiment, and in these situations Olsen/Bic-P should be as suitable as other commonly used measures of plant-available P (Scholefield et al., 1999).

The quantity of P that is available for uptake by plants from the soil is related to the concentration of P in the soil solution and P buffer capacity of the soil (Mengel et al., 2001). Phosphate buffer capacity is defined as the ability of a soil to maintain a constant solution P concentration in response to plant uptake (Mengel et al., 2001). Rapidly growing crops can take up anywhere between 0.7 to 1.0 kg P/ha/day (Russell, 1988) and soils with even relatively high available P concentrations may only have a solution P concentration in the vicinity of 1.0 to 7.1 kg/P/ha (Russell, 1988). Thus, in order for plant growth to be maintained solution P must be constantly replenished from the labile pool.

The optimum soil solution P concentration differs for individual crops and sites. Phosphate fertiliser rates applied to arable crops generally range from 20 to 80 kg P/ha according to crop species and the plant-available P concentration of the soil, although on soils with high P-fixing capacity rates of 100 to 200 kg P/ha may be applied (Mengel et al., 2001). In a UK study of 22 field experiments with potatoes, Allison et al. (2001) found that no yield benefit was attained when P fertilisers were applied to soils with an Olsen P value >26 mg/L. However, on a silt loam soil[3] in New Zealand, Prasad et al. (1988) found that maximum potato yield corresponded with an Olsen P ca. 70 mg/L in both years studied with a target value of 54-63 mg/L deemed optimal; target values for other crops ranged from >110 mg/L for winter spinach (*Spinacia oleracea* L.) to as low as 28 mg/L for sweet corn. Allison et al. (2001) showed increases in tuber numbers and yield were achieved when soluble P fertilisers were applied to soils with Olsen P <16 mg/L and 23 mg/L respectively. Therefore in organic cropping operations where the increase in plant-available P in response to PR application is small and delayed compared with water-soluble P_i fertilisers, it is probably highly unlikely that there will be a benefit in applying PR above an Olsen P of say 10 to 15 mg/L on sites other than those considered highly suitable for direct application of PR (see below).

[3] Yellow brown earth; similar to the soil used in the present study but with higher P-retention

The slow dissolution of PRs affects their ability to supply P to plants over the short term. In some situations PR is unable to support the same maximum yield as water-soluble P fertilisers due to inadequate dissolution of PR even at high rates of application (Kanabo and Gilkes, 1988c). Beneficiation by either synthetic or natural (allowable under organic regimes) processes increases the water-soluble fraction of PRs. The advantage of beneficiated PR is that more P_i is immediately available for uptake.

The efficiency of P utilisation from PR can differ markedly between plant species. For example, Zhu et al. (2002) found that in a sand-culture based system buckwheat (*Fagopyrum esculentum* M.) took up ten times more P from Ca bound sources (including PR) than (spring) wheat (*Triticum aestivum* L.). Likewise, Mathur and Lal (1989) found that SP was a better source of P for wheat, but PR was as good as SP for maize (*Zea mays* L.). Cowpea (*Vigna unguiculata* L.) was more responsive to PR than wheat (Maloth and Prasad, 1976). Haynes (1992) found that wheat and barley were less effective at utilising P from PR than buckwheat, rape and kale (*Brassica oleracea* L. Acephala), and this was put down to how these crops affect soil pH in the rhizosphere.

Some crops reduce soil pH in the rhizosphere, which enhances PR dissolution. For example, leguminous species excrete H^+ ions when fixing atmospheric N, which increases the dissolution of the PR (Gerke et al., 1995; Hinsinger and Gilkes, 1995), whilst others such as rape excrete organic acids (Hoffland et al., 1989; Montenegro and Zapata, 2002). The balance between cation and anion uptake also affects rhizosphere pH, and this can differ between crops (Haynes, 1992). Differences in root morphology and mycorrhizal interactions also play an important role in the different abilities of some crops to utilise P released from PRs (Li et al., 1991; Gahoonia et al., 1997), but because these are not areas of particular relevance to this study they shall not be discussed any further.

A more relevant question is whether or not large single (capital) applications of PR fertilisers are more agronomically effective than smaller annual applications and under

which circumstances. This comes down to a matter of economics, and given the slow release nature of PRs this needs to be considered over a number of years. Smaller annual applications incur larger application costs than larger, less frequent applications (Sinclair et al., 1993) but there is little information available on the frequency of PR applications required to maintain or increase plant-available P concentrations of the soil (particularly in cropping situations); which clearly depends on soil type and climate interactions and the method of application (Khasawneh and Doll, 1978).

One investigation on permanent pasture sites in Australia showed that yields were the same on 19 out of 23 sites when equivalent rates of PR were applied in one dose or spread out over four years (Garden et al., 1997). At one site in this study where the initial soil P concentration was very low, one large capital application out-yielded smaller annual applications because of increased pasture production in the early years. Simpson et al. (1997a) found that large, capital applications of (North Carolina) PR generally overcame the seasonal (PR dissolution and/or pasture yield) lag affects, leading to positive financial benefits compared with smaller annual applications. Scholefield et al. (1999) concluded PR fertiliser for the ley phase in a rotation should be incorporated in one dose at the outset rather than in smaller annual applications.

2.1.3 Fertiliser placement and incorporation

Banding water-soluble P fertiliser may enhance nutrient-use efficiency by reducing the amount of P that becomes fixed to soil surfaces. However, banding PR rather than broadcast and incorporating tends to reduce the rate of PR dissolution (Kanabo and Gilkes, 1988a) because dissolution is restricted by the build-up of the components that are released (i.e. P, Ca and OH^-; see section 2.2.3).

Granulation and band application increases the agronomic effectiveness of a water-soluble P_i but reduces that of PR (Kumar et al., 1993a). For example, full incorporation of PR resulted in the highest yield and P uptake of sorghum (*Sorghum bicolor* L.) (Madibbo, 1998); and full mixing of PR/S^o granules with soil increased the rate of PR

dissolution and total herbage production of perennial ryegrass (*Lolium perenne* L.) compared with non-mixed broadcast application (Rajan, 1983).

Clumping (Watkinson, 1994b) is a term that describes the uneven distribution of fertilisers in the soil following cultivation and may be a major concern where large (one-off) capital applications of PR occur. Although there has been no published work done on the effects of annual cultivation following large capital PR fertiliser applications, cultivation should theoretically "reactivate" PR dissolution by redistributing (clumped) fertiliser particles and diluting the products of dissolution. Clumping is an area of concern in the present study as some treatments used very high PR application rates (greatly exceeding those that would normally be used in the field).

2.2 PHOSPHATE ROCK DISSOLUTION AND AGRONOMIC EFFECTIVENESS

Dissolution of PR is a simple chemical reaction between apatite (the basic form of calcium phosphate present in PR) and hydrogen ions supplied by soil constituents (Kanabo and Gilkes, 1987b). Under appropriate conditions dissolution of fluor-apatite in PR (Equation 1) begins almost immediately following application to the soil, and progressively slows (Lee et al., 1987; Kanabo and Gilkes, 1988c; Dodor et al., 1999) as the products of dissolution (i.e. Ca^{2+} and $H_2PO_4^-$) build up. Conditions that assist the removal of the products of PR dissolution, such as plant uptake, P adsorption onto soil surfaces and leaching, increase the rate of dissolution.

Equation 1.

$$Ca_{10}(PO_4)_6F_2 + 12H^+ \rightarrow 10Ca^{2+} + 2F^- + 6H_2PO_4 + 12OH^-$$

The last 20 to 30 years has seen a lot of interest and investment in natural technologies that enhance the P-delivering power of PRs. More recently, most of this research has been geared towards the rapidly expanding international organic agriculture industry using various PR-solubilising fungi, bacteria, cyano-bacteria and actinomycetes to

increase agronomic effectiveness (efficacy to enhance crop growth) (Mba, 1994; Vassilev et al., 1996; Whitelaw, 2000; Arcand and Schneider, 2006; Vassilev et al., 2006). BioPhos, one of the fertilisers used in the present study was developed from this type of research. The co-application of PR and elemental sulphur (S^o), or BioSuper as it is commonly called, is another natural beneficiation process, but one that relies on acid production by S^o-oxidising bacteria rather than PR-solubilising micro-organisms. BioSuper was thoroughly researched throughout the 20th century, albeit mainly on pastoral farms. The technology behind and benefits of BioPhos and BioSuper are covered in greater detail in subsequent sections (2.3.1 and 2.3.2 respectively).

Despite a well developed understanding of the factors that affect PR dissolution and a large number of models that predict PR dissolution over a wide range of conditions published by various authors, e.g. (Kirk and Nye, 1986b; Mackay et al., 1986; Smalberger et al., 2006; Watkinson, 1994a), corresponding models that predict the resulting changes in plant-available P have not been published. Although most papers investigating PR dissolution first hand, e.g. (Hughes and Gilkes, 1986; Kanabo and Gilkes, 1988c; Rajan et al., 1991a), present some form of empirical model detailing the relationship between dissolution and changes in plant-available P these have not been incorporated into the dissolution models because of the complexity of the interactions between PR dissolution, changes in plant available P and the soil and climate conditions, time, plant uptake and the type of crop grown. Thus, unlike water soluble P_i fertilisers where changes in plant-available P are instant and easily and accurately predictable based on application rate and P-sorption capacity (P-fixation), changes in plant-available P following PR application are much more complex and not as easily or accurately estimated.

As well as the wide range of management factors influencing the effectiveness of directly applied PR (e.g. crop type, and fertiliser placement and incorporation; section 2.1), the key physical and environmental conditions/processes include:

- Reactivity and particle size of the PR.

- Proton supply/pH.
- Removal/build-up of the products of dissolution (P and Ca).
- Soil moisture

2.2.1 REACTIVITY AND PARTICLE SIZE

Phosphate rock reactivity is measured by solubility in a standard extractant solution such as 2 % citric acid or formic acid, or neutral ammonium citrate (NAC), and is an indication of how well it will perform in the field compared with other PRs (Rajan et al., 1992). The amount of P soluble from a given PR differs between the source/type of PR and extractants (Table 2.1). Hedley and Bolan (1997) stated that PRs with >30 % total P soluble in 2 % citric acid are 'reactive' and suitable for direct application. Bolland and Gilkes (1997) state that one containing more than 65 to 70 % of its total P soluble in 2 % formic acid is 'reactive'.

Sinclair et al. (1998) found that the agronomic performance of PRs for pasture was better related to their extractability by 2 % formic acid than by 2 % citric acid, and replacement of the standard 2 % citric acid test (commonly used in New Zealand) by the 2 % formic acid test was recommended. Two percent formic acid was also the best predictor of agronomic effectiveness in a study by Rajan et al. (1992) with a similar result found by Nying and Robinson (2006).

Table 2.1. Total P content and solubility in various chemical extractants of a range of different phosphate rocks (Rajan et al., 1992). * Sequential extraction values.

		% of total-P soluble				
		NAC-P*				
Phosphate rock	Total P content % w/w	1st	2nd	3rd	2 % Citric	2 % Formic
Sechura	13.1	19	23	23	33	67
North Carolina	13.0	15	19	17	31	56
Gafsa	12.8	13	17	17	31	56
Arad	14.3	11	17	15	29	48
Jordan	14.1	9	13	13	25	42
Nauru	16.7	7	6	5	17	19
Florida	14.0	6	8	9	17	18

Larger PR particles dissolve slower than smaller particles because larger particles have a lower specific surface area (m^2/kg) on which to react with the soil. Khasawneh and Doll (1978) found that the agronomic effectiveness of PR particles <0.15 mm was similar but for particles >0.15 mm PR effectiveness declines with increasing particle size. Stephen and Roberts (1983) found that a reduction in granule size from 2.0-2.8 mm to 0.25-1.0 mm improved perennial ryegrass yield significantly and powdered PR gave a further improvement. Likewise, granulation of PR particles reduced agronomic effectiveness of (North Carolina) PR (Kumar et al., 1993a).

Phosphate rock dissolution is inversely proportional to the square of the particle diameter. For example, Watkinson (1994b) calculated that for a typical North African/Middle East PR it would take around 0.6 yrs for a particle of 0.075 mm diameter to dissolve when mixed with soil with a dissolution rate constant (α_1) of 0.0025 mm^2/year, and four times longer for a particle with twice the diameter. Because PR particle size is negatively correlated with solubility in the standard extraction solutions (Rajan et al., 1992) particle size is inherently accounted for during the measurement of PR reactivity.

2.2.2 PROTON SUPPLY

The ability of a soil to supply protons is one of the key drivers of the rate of PR dissolution. Proton supply to the soil solution is dependent on both the pH and the titratable acidity. However, because the relationship between soil pH and titratable acidity is near linear, pH alone should be a good predictor of proton supply to the soil solution (Kanabo and Gilkes, 1987b).

There are numerous studies that show the importance of soil pH on PR dissolution. For example, in a short term (7 day) laboratory study Kanabo and Gilkes (1987b) found that PR dissolution decreased with increasing pH (see also Barnes and Kamprath, 1975; Hughes and Gilkes, 1984; Khasawneh and Doll, 1978). But in one study investigating 30

soils with differing pH treated with PRs of differing reactivity, Mackay et al. (1986) found that soil pH did not feature as an important variable influencing PR dissolution, and that Ca^{2+} in the soil solution and P-sorption capacity was of much greater importance. Despite the findings these authors acknowledged that soil pH cannot be completely ignored as a factor affecting PR dissolution because of the sheer volume of work to the contrary found by other authors; yet it remains unclear why pH was not a factor in this study.

Increased dissolution as a result of lower pH tends to enhance the response to applied PR. Rajan et al., (1991b) found a negative relationship between soil pH and pasture yield. This was related to increases in PR dissolution and Olsen P with decreasing pH. Similarly when PR was applied, a reduction in soil pH from 6.2 to 4.2 produced four-fold higher yields of triticale (*x Triticosecale* W.*)* grown for 30 days (Kumar et al., 1993a).

Soil pH fluxes often behave differently in laboratory and field studies. In laboratory studies, soil pH tends to increase over time following the addition of PR as a result of proton consumption (liming effect), but after a period of time tends to revert towards its initial pH (Rajan and Edge, 1980; Kanabo and Gilkes, 1988c). However, in field conditions, Lewis et al. (1997) found that PR application had little or inconsistent effects on soil pH and this may be attributed to uncontrolled (acidifying) variables such as N-leaching, plant uptake of a NH_4^+ and nitrification. Nitrification can cause a marked lowering of soil pH in laboratory studies and to avoid this anti-microbial agents such as toluene are often added to the soils.

2.2.3 PRODUCTS OF DISSOLUTION

Accumulating concentrations of the products of PR dissolution (P and Ca) have a negative effect on dissolution. The Ca exchange and P buffering capacity of the soil play a major role in moderating the solution P and Ca concentrations.

Babare et al. (1997) found that the dissolution of (North Carolina) PR was positively correlated to P-buffering capacity but that increases in plant Bic-P were lower in soils with higher P-buffering capacity. Kanabo and Gilkes (1987c) found that increasing the P-buffering capacity of the soil by 9 % (by adding synthetic goethite) resulted in a 107 % increase in PR dissolution but a 54 % decrease in Bic-P, and reduced dry weight yield and P content of subterranean clover (*Trifolium subterraneum* L.) tops by 19 % and 34 % respectively. A similar study by the same authors (Kanabo and Gilkes, 1987a) produced similar results. Although these studies demonstrate that increasing the P-sink of the soil increases the rate of PR dissolution, there is strong evidence that the plant-availability of the dissolved P is reduced.

Calcium saturation is strongly correlated with Ca-buffering capacity and was the single most important variable affecting dissolution of (Sechura) PR, by itself explaining 45 % of the variation of PR dissolution in 30 soils (Mackay and Syers, 1986). The second most important variable was P sorption capacity and together with Ca saturation explained 65 % of the variation in PR dissolution. Nying and Robinson (2006) found that Ca saturation of cation exchange sites (and proton supply) strongly affected PR dissolution. Agbenin (2004) found that at pH ≥5.5, PR dissolution was more constrained by Ca^{2+} ions in solution than by availability of protons. Increasing solution Ca concentration caused a decrease in the dissolution of PR (Robinson and Syers, 1991). These studies indicate that management practices that increase Ca-sinks (e.g. increasing soil organic matter content) and the supply of protons to the soil are beneficial to PR dissolution.

Phosphate rock dissolution may be enhanced in the rhizosphere and the removal of Ca and P through plant uptake and the supply of protons or the release of organic anions by plant roots (see section 2.2.2) are the main reasons for this (Bolan et al., 1997).

2.2.4 SOIL MOISTURE AND TEXTURE

Soil moisture is another key driver of PR dissolution (Kanabo and Gilkes, 1988b). Evans et al. (2006) found that fluctuations in soil moisture affected Olsen P fluxes more than changes in soil temperature. In a study in Eastland, New Zealand (Craighead, 2004), summer rainfall was considered the most important driver of PR dissolution (and oxidation of S^{o}). Bolland (1995) found that the amount of PR required to produce the same relative yield of white clover (*Trifolium repens* L.) decreased with increasing rainfall/soil moisture.

Gillard et al. (1997) stated that for highly reactive PRs (formic soluble P > 70 %) a total annual rainfall of 700 mm to 1000 mm (depending on soil type) is required for them to be agronomically effective; for moderately reactive PRs (undefined) 900 to 1200 mm was required. However, these estimations were based on topical PR applications and therefore may overestimate the amount of rainfall required for adequate dissolution to occur when PRs are incorporated into the soil during cultivation.

Phosphate rock dissolution occurs even in very dry soils, increasing up to field capacity, after which little further dissolution occurs (Kanabo and Gilkes, 1988b). These authors found that over a 280 day period, PR dissolution increased from 4 % for air-dry soil to 13 % for a gravimetric moisture content (MC) of 12.5 % (w/w), increasing to about 17 % at 100 % gravimetric MC. The effect of wet-dry treatments was also investigated by Kanabo and Gilkes (1988b) and a short drying period did not substantially affect PR dissolution or Bic-P concentrations.

Phosphate rock generally dissolves faster in finer textured soils. Kanabo and Gilkes (1988d) found that PR dissolution and Bic-P increased with an increasing proportion of < 45 µm particles, however, a smaller proportion of dissolved P was recovered by the

bicarbonate extractant for the soil comprising only the < 45 µm particles. This was thought to be due largely to the greater P-sorption capacity of the fine grained soil constituents. In a study of 228 soils from the main agricultural areas of Western Australia, Hughes and Gilkes (1994) found that the most suitable soils for topical applications (i.e. to the soil surface) of PRs are sandy soils and those high in organic matter (i.e. humic or peaty podzols) where much of the dissolved P remains available to plants. Sale et al. (1997) found similar results for Northern Queensland, but in southern NSW (where there is less rainfall and therefore the soil surface dries out much quicker) sandy soils slowed PR dissolution.

2.2.5 TIME

There have been numerous studies investigating the dissolution of PR and subsequent changes in soil chemistry over time. The rate of PR dissolution tends to decrease over time following Mitscherlich-type models (Equation 2); see Mackay et al. (1986) and others (Wright et al., 1992; Agbenin, 2004), although Kanabo and Gilkes (1988b) showed sustained slow rate of dissolution long after the period of rapid dissolution (Figure 2.1).

Equation 2

$$\Delta P = A(1-e^{-cx})$$

where ΔP is the amount of P released from the rock phosphate at time X; A is the asymptote and C the curve fitting parameter (Mackay et al., 1986).

The change in Bic-P over time is strongly correlated with the amount of P dissolved from the PR, although a clearer more defined asymptote is apparent (Figure 2.1). In some studies Bic-P decreases after a period of time despite ongoing dissolution because the rate of P released is unable to replenish P lost to P-fixation (Kanabo and Gilkes, 1988b).

Phosphate rock dissolution in the field usually proceeds at a much slower rate than in the laboratory (Robinson and Syers, 1991) because of different experimental conditions. For example, laboratory assays are generally carried out on sieved (i.e. small aggregates; high surface area), air dried soils where the PR has been evenly spread through the soil and incubated at constant, near optimal temperature and moisture regimes. Field studies however, have typically had topical applications (as mentioned above) or when incorporation of the PRs into the soil has occurred this has been done with agricultural equipment, on cloddy soils (large aggregates; low surface area), which reduces the homogeneity of the mixing causing clumping (above), and along with variable (sometimes sub-optimal) temperature and moisture regimes, act to slow the rate of dissolution.

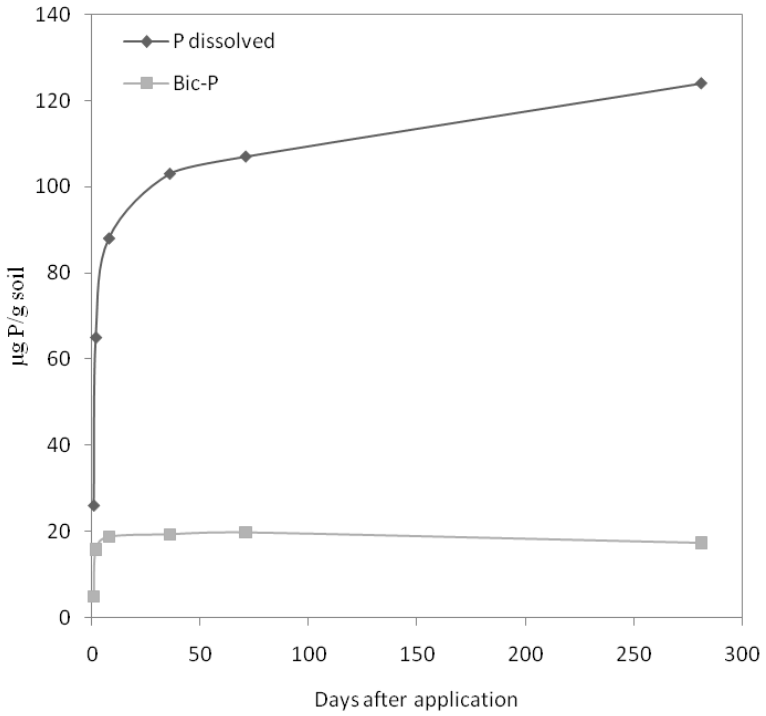


Figure 2.1. Changes over time in the amount of P dissolved and Bic-P from phosphate rock applied at 800 µgP/g soil (Kanabo and Gilkes, 1988b).

2.2.6 APPLICATION RATE

As application rate increases the proportion of PR dissolved decreases, yet the absolute amount dissolved increases (Hughes and Gilkes, 1986; Kanabo and Gilkes, 1988c; Rajan et al., 1991a). However, this relationship is not linear. For example, a ten-fold increase in the rate of PR application (from 200 to 2000 µg P/g soil) resulted in a four-fold decrease in the relative amount (percentage) of PR dissolved (Kanabo and Gilkes, 1988c). The amount of PR dissolved could be described by the same exponential response function as Equation 2, except that x = the rate of PR applied (µg P/g soil) (Kanabo and Gilkes, 1988c). Increases in Bic-P arising from the dissolution of PR are described by the same exponential equation but with different parameter values (Kanabo and Gilkes, 1988c). Over the incubation periods tested in this (Kanabo and Gilkes, 1988c) study, asymptote values of dissolved P ranged from 28 to 93 µg P/g soil and the asymptote values for Bic-P from 4 to about 18 µg P/g soil (for one and seven days respectively).

2.2.7 MEASURING PHOSPHATE ROCK DISSOLUTION

Because PR dissolves slowly in soil it is desirable to know the amount of PR that has dissolved as it provides an insight into how much and how often future applications of PR should be. In a scientific context it enables estimation of the rate of PR dissolution along with the factors that influence it.

The wide range and complexity of P-sorption reactions makes direct measurement of dissolved P (PR dissolution) impractical, so indirect measurements are required. There are a number of ways to indirectly measure PR dissolution in soil including i) fractionation, ii) dilute acid extraction, iii) alkaline extractions, iv) anion exchange resins, v) P^{32} isotopic exchange, and vi) difference in exchangeable Ca. As reviewed in Khasawneh and Doll (1978), each system has its pros and cons.

The difference in exchangeable Ca technique (ΔCa; used in the present study) has been widely and successfully used to quantify the extent of PR that has dissolved following

application to soil, particularly in laboratory studies. When Ca is released during PR dissolution, it is attracted to the cation exchange sites on soil particles and is easily extracted/displaced using buffered cationic extractants such as $BaCl_2$ (Bascomb, 1964; Hughes and Gilkes, 1984; Wright et al., 1991). Differences in extractable Ca between the untreated (control) and treated (PR applied) soils enable an estimation of the amount of P that has dissolved, assuming congruent dissolution of P and Ca from apatite/PR. The main limitation of this method is the potential for high native amounts of exchangeable Ca and $CaCO_3$ impurities in the PR to also be extracted, which can affect the accuracy of the estimations of PR dissolution (Khasawneh and Doll, 1978). Furthermore, the potential for drainage and leaching (Bolan and Hedley, 1989), eluviations, and bioturbation (Kumar et al., 1993b; Loganathan et al., 2004), and plant uptake of Ca, P_i and/or PR particles from the fertiliser application/sampling zone makes this technique unsuitable for field experiments. Where PR dissolution is being studied in the field, the amount of residual P or Ca extracted using 1M HCl was recommended (Bolan and Hedley, 1989).

Changes in exchangeable Ca due to PR dissolution are strongly correlated with changes in Bic-P (Hughes and Gilkes, 1994; Kanabo and Gilkes, 1988c). As mentioned above Olsen P is currently the most commonly used method for estimating plant-available P in New Zealand, but it has been shown to underestimate the amount of plant-available P in systems with a history of PR application (Saggar et al., 1999). Resin P (Saggar et al., 1999) and Bray P (Syres et al., 1981; Saggar et al., 1999) are considered to give a closer approximation of plant-available P in some such circumstances, but not others (Kumar et al., 1992b; Simpson et al., 1997b). The increase in plant-available P is not a reliable measure of PR dissolution because a varying proportion of the P released from the PR is extractable by any given extractant, depending on the (soil) conditions (e.g. pH, P-retention). Furthermore, as PR application rate increases a lower proportion of the P dissolved from the PR may be recoverable by the (bicarbonate) extractant (Barrow and Shaw, 1976).

2.3 BENEFICIATION OF PHOSPHATE ROCK USING ORGANICALLY APPROVED METHODS

The dissolution and agronomic efficiency of PRs can be enhanced using a range of organically approved methods. These range from treating the PRs themselves, seeds or soils with PR-solubilising micro-organisms; applying PR in conjunction with acidifying compounds such as S^o, with or without inoculation with S^o-oxidising micro-organisms (e.g. *Bacillus thioxidans*); or composting the PRs with organic material, with or without PR-solubilising micro-organisms. Much work has been undertaken over the last few decades on these types of natural beneficiation processes with varying degrees of success. Probably the most acclaimed system has been the co-application of PR and S^o (BioSuper), now common practice both in conventional and organic agriculture.

Phosphate rock solubilising bacteria have been shown to increase P uptake and crop yield. Strains from the genera *Pseudomonas*, *Bacillus, Aspergillus* and *Rhizobium* are among the most powerful phosphate solubilisers (Rodriguez and Fraga, 1999; Reddy et al., 2002). Solubilisation is enhanced by the production of organic acids from these micro-organisms (Shin et al., 2005). Innoculation of PR with various phosphate solubilising micro-organism isolates increased soybean (*Glycine max* L.*)* nodulation, plant growth, grain yield and uptake of N and P but the uninoculated PR treatment did not (Singh and Singh, 1993). Similar results were found for wheat (Singh and Kapoor, 1999) and mungbean (*Vigna radiata* L.) (Singh and Kapoor, 1998), indicating that this type of approach can be beneficial on a range of crops.

Sheshadri et al. (2004) found that the phosphate solubilising abilities of ten *Aspergillus niger* strains were affected by the source of N and C, as did Vora and Shelat (1998) on three bacterial and one yeast species (viz. *Bacillus circulans, B. brevis, B. coagulans* and *Torulospora globosa* respectively). This indicates that the conditions in which the micro-organisms grow have a direct affect on their ability to solubilise PR.

The following two sub-sections review and provide information on the two products/treatments used in the present study that were subjected to a natural (non synthetic; organically acceptable) beneficiation process; BioPhos and BioSuper.

2.3.1 BIOPHOS

BioPhos is an organically approved PR fertiliser product. Since the present study was initiated (July 2004) the manufacturing of BioPhos has been taken over by Ballance Agri-Nutrients Ltd from Sieber Technologies Ltd. One of the outcomes of this is that BioPhos is now only available from Northland, Waikato and Manawatu depots. The current price of BioPhos is $485 /t.[4]

BioPhos is made by mixing PR with seafood offal, inoculating the mixture with PR-solubilising micro-organisms and composting. Information was not available on the types of micro-organisms used or the conditions used during the composting, nor was the change (if any) in physical or chemical composition or stability, which would theoretically affect reactivity and agronomic efficiency. The chemical characteristics of BioPhos are set out in Table 2.2.

Table 2.2. Chemical analysis of BioPhos, from: ^Sinclair (2002); *Ashcroft et al. (2004).

Nutrient component	Percent w/w
Total P*	9.6
P as water-soluble*	<0.5
P as citrate soluble*	1.6
P as citrate insoluble*	7.6
Total K*	8.0
Total S*	6.4
Total Ca*	25.6
Total N^	0.2
Organic matter^	5.0

[4] http://www.ballance.co.nz (accessed 14 August 2008).

An unpublished study (Chitralekha et al., 2002) showed that after 60 days, soil solution P concentrations were greater in an allophanic soil treated with 800 mg P/kg soil of BioPhos than with the same rate of SP (Figure 2.2).

There has been only one published report on the effects of BioPhos, or Fish-P as it is called in Ashcroft et al. (2004), on crop growth and yield. In this study, SP and BioPhos were applied separately at 120 kg P/ha onto raised beds and incorporated to a depth of 10 cm. There were 12 replicates of each treatment arranged in randomised blocks. Rainfall data over the experimental period was not presented. Soil Olsen P at the start of the experiment was 8 mg/L in the 0-15 cm depth and 5 mg/L in the 15-30 cm depth; similar to the levels found in the present (field) study (Chapter 4). Processing tomatoes (*Solanum lycopersicum* L. cv. Heinz 9035) were grown over two years. The crops were sampled on two occasions each year (mid season and end of season). Various measurements were undertaken on each sample date including plant height and width; dry weight of the above ground/shoot material; yield of green, ripe and rotten fruit; average weight, soluble solids, pulp colour and juice pH of the ripe fruit. Nitrogen fertilisation and other crop management inputs were based on standard commercial practices. Although there was no mention in the text of this report on any attempt to mitigate against the N included in the BioPhos, the amount applied was negligible (2.5 kg N/ha based on 9.6 % total P, 0.2 % total N and 120 kg P/ha; Table 2.2).

Crop data from this (Ashcroft et al., 2004) study are shown in Table 2.3. Both P fertilisers consistently produced more total shoot biomass and fruit and fruit solids yield than the control but there were no significant differences in fruit yield or quality between fertiliser treatments. No data were presented or discussion made on changes in soil chemistry and/or nutrient availability and uptake.

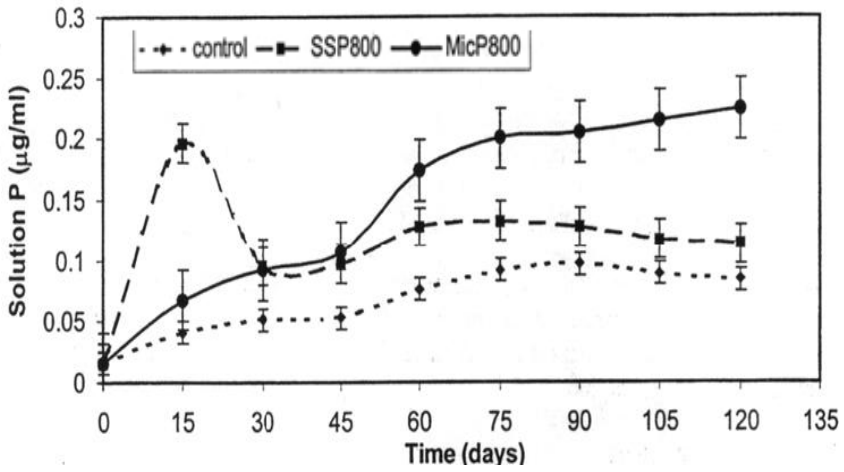


Figure 2.2. Changes in soil solution P after application of 800 mg P/kg soil of single superphosphate (SSP) and BioPhos (MicP) compared with no fertiliser (control) (Chitralekha et al., 2002). Permission to use this figure obtained from Clive Sinclair (www.biofert.co.nz).

One point worth mentioning from this (Ashcroft et al., 2004) study was that a high fruit yield in one of the control plots and a low yield in one of each of the fertiliser treatment plots were treated as outliers and excluded from the analysis. No attempt was made to compare the results with these outliers included in the analysis which were blamed on problems with irrigation.

Table 2.3. Tomato yield and quality components for single super phosphate (SP) and BioPhos applied at 120 kg P/ha (Ashcroft et al., 2004). Note the control had no P applied.

	Year 2				Year 2			
Treatment	Total shoot (g/plant)	Total fruit (t/ha)	Ripe fruit (t/ha)	Fruit solids (t DM/ha)	Total shoot (g/plant)	Total fruit (t/ha)	Ripe fruit (t/ha)	Fruit solids (t DM/ha)
Control	204.4	99.7	88.8	4.17	269.0	77.3	69.1	3.14
SP	233.2	115.4	102.6	4.88	436.0	99.1	87.4	3.79
BioPhos	232.7	115.2	102.8	4.88	383.0	107.4	95.9	4.17
$LSD_{0.05}$	49.1	10.9	10.3	0.46	69.5	17.0	15.1	0.61

There have been other unpublished studies (Sinclair, 2002) commissioned by Sieber Technologies Ltd examining its effectiveness as a P fertiliser on various crops including pumpkin (an undisclosed species of *Cucurbita* L.; experiments conducted at Hastings

and Levin, New Zealand) and sweet corn (Hastings only). In these studies there were no details provided on the experimental design, methods used for the measurements taken, or statistical analysis undertaken to support the data.

Nevertheless, in these studies pumpkin grown at Hastings that received BioPhos (blended with Moana Natural [MN]; a fish based foliar fertiliser) apparently yielded 1.0 kg per plant (38 %) more fruit than the control (no fertiliser) plot(s) and 0.8 kg per plant (28 %) more than the SP/Nitrophoska plot(s), with similar increases apparent for the seed yields. At the Levin pumpkin trial there were no control data presented yet BioPhos+MN reportedly yielded 1.3 kg/plant (38 %) more fruit than the SP/Nitrophoska plot(s). Sweet corn grown with BioPhos at Hastings was reported to yield 6.0 t/ha (22 %) more cobs than the control and 7 t/ha (27 %) more than SP.

There is more data available on pasture yields from similar studies commissioned by Sieber Technologies Ltd with similar plant responses to the studies mentioned above, but given the lack of detail on experimental design or statistical analysis, coupled with the fact that the relevance to cropping situations is questionable, there is little benefit in discussing these studies.

With this limited amount (and often anecdotal) information available, growers and fertiliser consultants clearly do not have enough information on the conditions and applications rates required for BioPhos to meet crop production targets, thus further work is required.

2.3.2 BIOSUPER

A lot of soils are not well suited for direct application of PRs (e.g. high pH, low CEC) and in these circumstances some sort of beneficiation is required. The positive effect that co-application of PR and S^o has on PR dissolution and agronomic efficiency is well documented and is commonly known as the "bio-super effect".

Elemental S is oxidised by *Thiobacilli thioxidans*, creating sulphuric acid. This can occur in two ways, i) *in-vitro* digestion, which involves an incubated digestion of a blend of PR and S^o inoculated with *T. thioxidans*, and a protein source (Ghani and Rajan, 1995) or ii) directly applied, which involves applying a blend of PR and S^o and relying on the native *Thiobacilli* spp. in the soil for S^o digestion (Lee et al., 1987).

Ghani et al. (1994) found that a 4 week *in-vitro* digestion of PR+S^o inoculated with *T. thioxidans* and a nutrient-enriched microbial substrate (lactic casein whey; pH 4.5) incubated for 6 weeks at 30^{o}C and 21 % MC, produced a PR fertiliser product with around 0.8 % water-soluble P, which is equivalent to 9-10 % partially acidulated PR (i.e. 9-10 % of the stoichiometric amount of sulphuric acid needed for complete digestion of the PR). This was achieved with around 14 % of the added S^o being oxidised. On testing in the field, Ghani and Rajan (1995) found that after a 6 week digestion the PR+S^o blend had an agronomic effectiveness equal to that of 60 % partially acidulated PR.

In some studies BioSuper has been shown to be as good as, if not better than SP (Rajan, 1983; Stamford et al., 2007), and this may be influenced by the ratio of PR to S^o. Rajan (1983) found that perennial ryegrass herbage yield and phosphate uptake using a 5:1 blend of PR+S^o was as effective as SP, with the uptake but not the yield decreasing slightly when the PR:S ratio was 6:1, and both were considerably reduced when the ratio was 7:1.

In a recent study (Stamford et al., 2007), *in-vitro* digestion of PR with increasing proportions of finely ground S^o inoculated with *Thiobacilli* spp. significantly enhanced

the 'available P' (Barreto et al., 1997)[5] content (not shown) and reduced the pH of the PR+S^o mixtures (Table 2.4). In this study, yam bean (*Pachyrhizus erosus* L.) produced significantly higher total shoot biomass than the control when P was applied at 100 kg P/ha, regardless of form/fertiliser type and PR+S^o blends inoculated with *Thiobacilli* spp. produced similar yields to TSP and significantly higher yields than PR applied on its own. Furthermore, soil plant-available P (Barreto et al., 1997)[6] concentrations at 90 days after application were higher when the PR+S^o mixtures under went *in-vitro* digestion with *Thiobacilli* spp. than when they did not, and increased as the ratio of S^o to PR increased.

Dissolution of PR and S^o and subsequent changes in Bic-P are affected by the number of S^o-oxidising heterotrophic bacteria in the soil, which is affected by soil type (Lee et al., 1987). This has important implications for directly applied blends of PR+S^o. Gley soils were the poorest oxidisers of S^o (44 % oxidised after 70 days). Organic soils were best (90 %). Yellow brown loams oxidised 82 % of applied S^o.

Table 2.4. Total (yam bean; *Pachyrhizus erosus* L.) shoot biomass and pH of various fertiliser mixtures of PR and elemental sulphur (S) with or without *Thiobacilli* spp. (*Tb*) after 60 day *in-vitro* incubation; and changes in plant-available P and soil pH after 90 days where 100 kg P/ha was applied (Stamford et al., 2007). Values with the same letter are not significantly different (P <0.05).

P fertiliser	Shoot biomass (g/plant)	Fertiliser pH	Soil available P (µg P/g)	Soil pH
PR	5.53a	5.1	5.7d	6.4a
PR+S (5:1)	5.77ab	5.2	8.0cd	6.3a
TSP	6.30a	5.0	12.4bc	5.9b
PR+S (20:1) +Tb	6.13a	5.0	16.9b	5.7bc
PR+S (10:1) +Tb	5.57ab	4.3	19.1ab	5.5c
PR+S (7.5:1) +Tb	6.06a	4.1	21.6a	5.4cd
PR+S (5:1) +Tb	5.97ab	4.0	24.1a	5.3d
Control	4.70c	NA	0.3e	6.0b

[5] The method was not mentioned in Stamford et al. (2007) but is (apparently) detailed in Barreto et al. (1997).
[6] As for the previous footnote.

2.4 SUMMARY

East Coast Organic Producers Trust growers are struggling to produce economic crops on anything other than small-scale (home) gardens for a number of reasons including poor soil fertility, and poor weed, pest and disease control. However, virtually every ECOPT paddock had a low Olsen P concentration, usually somewhere around 6 mg/L. Organic principles and regulations stipulate that only naturally occurring substances can be applied to organic production systems. Thus, the ECOPT need readily available forms of organic-approved P fertilisers to increase the P status of their soils. Phosphate rock based fertilisers are the ideal candidate and have the added advantage of supplying Ca, which is also low in some ECOPT grower's soils. However, there should be no illusion that increasing plant-available P concentration of the soil by itself will greatly increase production levels. Increased production will be greatest when effective weed, pest and disease control systems are also implemented.

Optimal (target) soil test values for Olsen P in New Zealand vary with crop species by up to 83 mg/L as shown by Prasad et al. (1988). Plant responses to directly applied PR fertilisers are often delayed, only becoming apparent in the second or third season after application. However, in an ideal environment plants can respond to PR applied immediately before sowing, but this is strongly dependent on the conditions (e.g. soil, climate and PR reactivity, application rate, incorporation etc), and immediate responses are usually only seen when plant-available P concentrations are very low. Furthermore, some plant species are better able to utilise P from PR, and these plants are typically ones that exude acids or lower the pH of the rhizosphere such as legumes and rape.

Phosphate rock is a naturally occurring, readily available, high analysis source of P and is the primary source of P fertiliser in organic production systems. However, even the most reactive PRs are only slowly soluble in soil. Phosphate rock dissolution rate is influenced by a number of chemical, physical and environmental factors. Dissolution increases with: decreasing pH, solution Ca and P concentration, and fineness of the PR

particles (but only for particles >0.15 mm; below this there is little effect); and with increasing proton supply, pH buffer capacity, Ca exchange capacity, P buffer capacity (fixation), (spatial and temporal) contact with soil, and soil moisture (up to field capacity, after which there is no further increase).

A soil pH below 5.8 is required for adequate dissolution to occur, but very low pH can increase the availability of Al and Fe, precipitating the additional P released making it unavailable to plants. High soil P-fixation increases dissolution rates but again much of the P released is adsorbed and therefore unavailable to plants. One way of ensuring adequate dissolution without excessive P being fixed or precipitated is to increase the Ca exchange capacity of the soil by increasing soil organic matter levels. This effectively lowers solution Ca concentrations thereby promoting dissolution whilst maintaining elevated solution P and plant-available P concentrations.

Studies using topical applications of PRs have shown that for optimal dissolution annual rainfall should be greater than about 800 mm/year but this may be lower when PRs are incorporated into the soil. Rainfall in the ECOPT region is around 1000 mm/year. Incorporating PRs with the soil increases the dissolution rate by increasing contact with the reactive components of the soil but at the same time increases exposure to sorption processes. Some studies show that banding can be useful but this only appears suitable with highly reactive PRs and/or those applied along with S^o (BioSuper).

Beneficiation systems that utilise phosphate-solubilising and/or S^o-oxidising micro-organisms will be beneficial particularly where conditions for PR dissolution are less than optimal, or where more rapid PR dissolution is required. In a cropping situation faster dissolution rates are best so beneficiated PRs will probably be more suitable. However, determining the most cost-effective form of beneficiation for cropping situations requires further work.

Phosphate rock and S^o blends can be incubated for extended periods (e.g. 6 weeks) along with *Thiobacilli* spp. and a suitable nutrient-enriched substrate to partially acidulate the PR prior to application, or they can be applied directly to the soil and the native soil micro-organisms (which include *Thiobacilli* spp. in varying amounts depending on the soil) oxidise the S^o and acidify the soil environment. The incubated PR+S^o blend has advantages over the directly applied blend in that it is already partially acidulated prior to application and therefore tends to have a more immediate effect. Inoculation of PR, soil or seeds with phosphate solubilising micro-organisms (e.g. *Bacilli* spp. and *Aspergillus* spp.) has shown to be a promising way of increasing plant-available P from PRs, and from P fixed in the soil. These micro-organisms typically acidify the environment in which they grow thus releasing P. Composting PRs with these kinds of micro-organisms along with a suitable nutrient source (e.g. fish offal) and applying to the soil has been shown to provide significant benefits to processing tomato and (anecdotally) other crops (e.g. sweet corn and pumpkin).

Large capital applications of PR are often found to provide benefits over smaller annual applications, both in yield response and savings in applications costs. There have been many attempts to construct dissolution models with varying degrees of precision and all of which have their limitations. Furthermore, predicting dissolution rates is one thing but predicting the increases in plant-available P and crop response to this has proved difficult given the numerous interactions and chemical transformations of P in the soil. Moreover, these dissolution models do not include the beneficiated forms of PR such as BioPhos and BioSuper. Although a small amount of research has been done on the use of BioPhos as a fertiliser in New Zealand this has not been published. Therefore, there is still the need for field research to fine tune PR-based fertiliser application strategies particularly on organic cropping farms.

On organic cropping farms phosphate rock is usually applied at low rates aimed at maintaining the soil P concentration rather than increasing it (Evans et al., 2006). Because the overarching aim of this study was to elucidate the optimum economic

application rate and the best ways of increasing plant-available P concentrations of the ECOPT's soils a wide range of application rates of various, readily available PR based fertilisers will need to be tested. Rates over 1,000 kg P/ha (e.g. application rate 5; 1,333 mg P/kg soil; Table 3.1) would be considered at the extreme upper end of P fertiliser application, equating to fertiliser application rates close to or exceeding 10 t/ha (depending on the P content). Clearly the logistics of transporting and spreading of this amount of fertiliser may be considered prohibitive by many growers, but in this case the remoteness of the ECOPT growers from the nearest fertiliser depots, could potentially make larger less frequent applications more cost effective.

CHAPTER 3

3 LABORATORY STUDY

3.1 OVERVIEW

This chapter presents the results obtained from a laboratory experiment aimed at determining the rates of dissolution and subsequent changes in soil pH and plant-available P (measured as Bic-P) for three PR-based fertilisers.

Soil was collected from an organic certified farm located at Tikapa, Eastland, New Zealand; the same site as the field experiment (Chapter 4). The PR fertilisers tested were Ben Guerir RPR, BioPhos (a microbially beneficiated form of PR), BioSuper (a blend of Ben Guerir RPR and S^o in a 5:1 ratio applied directly to the soil). Triple superphosphate (TSP) was included but only as a reference for water-soluble P fertilisers. These were mixed with soil at various rates and incubated at 15^{o}C and 29 % MC (w/w) for 155 days. Measurements of fertiliser dissolution (using the ΔCa technique), soil pH and Bic-P were undertaken at various times over the incubation period.

Results followed expected trends. Increasing PR application rate lead to a decrease in the percentage of applied P that dissolved but an increase in the absolute amount (mg) that dissolved. Bic-P increased with increasing application rate. However the increase in Bic-P (ΔBic-P) was less than the amount of P released during dissolution. For RPR, $\Delta Bic\text{-}P = 0.051x$ (R^2 = 0.95), for BioPhos $\Delta Bic\text{-}P = 0.153x$ (R^2 = 0.83) and for BioSuper $\Delta Bic\text{-}P = 0.084x$ (R^2 = 0.37); where x is the amount of dissolved P (mg P/kg soil).

Data were analysed using ANOVA. The maximum increase in Bic-P occurred at the highest application rate (1333 mg P/kg soil); 155 days after fertiliser application (DAFA) for the PR fertilisers and 3 DAFA for TSP. Of the PR fertilisers, BioSuper produced the greatest increase in Bic-P whilst RPR and BioPhos were not significantly different.

An exponential model in the form of $y = -B(1-R^x)$ was used to describe the dissolution and subsequent changes in Bic-P (y) of the PR fertilisers over time (x; with B and R being curve fitting parameters/constants). Models of PR dissolution and changes in Bic-P fitted the data well; with predicted vs. observed R^2 values of 0.93 and 0.97 respectively. Triple superphosphate was not included in the analysis or modelled as it was not intended to be used in the field experiment. Values for the B parameter were correlated with application rate. The relationship for RPR and BioPhos was $B = -4.97\ ln(x)+18.54$ and for BioSuper $B = -0.02x–2.68$, where x = application rate (mg P/kg soil). Values for the R parameter were not correlated with application rate.

Apart from a slight increase over the first few days, soil pH dropped in most treatments throughout the course of the experiment. This was probably the result of nitrification, although it was not measured. From 22 DAFA onwards RPR and BioPhos applied at 1333 mg P/kg soil had a significantly higher soil pH relative to the Control, whereas from 57 DAFA onwards BioSuper had a lower pH than the Control as a result of S^o oxidation.

Data indicate that application rates of between 267 and 1333 mg P/kg soil are the most suitable rates for use in field experiments on this soil, because at rates lower than these significant differences among treatments in Bic-P would be difficult to detect, especially under field conditions.

3.2 OBJECTIVES

The aim of this study was to provide guidance on the rates to use in the field experiment and to generate models for the dissolution and changes in soil pH and Bic-P of the three PR-based fertilisers. The PR dissolution and soil pH data were to be used to help explain the changes in Bic-P over time and differences in Bic-P among treatments. Ultimately, the Bic-P models were to be calibrated for field conditions using the data from the field experiment.

3.3 METHODOLOGY

A Hikuwai fine sandy loam (Umbric Dystrochrept) top soil (Rijkse, 1980) was collected from the same paddock that the field experiment was to be conducted in. The field-moist soil was passed through a 2 mm sieve and air-dried at room temperature. The following measurements were then undertaken: P retention, organic carbon, exchangeable bases (Ca, Mg, Na, K), pH (1:2.5 H_20) and sulphate S; using standard (New Zealand) techniques (Blakemore et al., 1987). Total soil porosity was measured by displacement and particle size distribution by dry sieving. Bic-P was also measured (see below for methodology).

Ben Guerir RPR (RPR; ex. Ravensdown), BioPhos (BioP; ex. Sieber Technologies Ltd) and S^o (ex. Ravensdown) were passed through a 250 µm sieve to remove the larger, less reactive particles. Triple superphosphate was ground using a mortar and pestle before being passed through a 250 µm sieve. Total P and Ca content, 2 % formic-acid solubility and particle size distribution was determined for RPR and BioPhos. Total P analysis was done using a nitric and hydrochloric acid digestion followed by colorimetry using the vanado-molybdate method (Anon, 1983); Ca analysis was done using a nitric and hydrochloric acid digestion followed by ICP-OES analysis (Hamalova et al., 1997); the formic-acid extraction followed the method of Hoffman and Mayer (1953) which was analysed for P using ICP-OES (Hamalova et al., 1997); and particle size distribution was measured by dry sieving. Triple superphosphate was not analysed as it was included as a reference for water-soluble P fertiliser only.

3.3.1 TREATMENT PREPARATION

The fertiliser application rates used were based on the expected trends in PR dissolution and subsequent changes in Bic-P and what was economically and physically achievable in the field considering transport and bulk-spreading.

Twelve fertilised soil treatments (Table 3.1) were prepared. For each, 80 ml of distilled water was added to 480 g of air-dried soil. A measured quantity ($^+/_-$ 5 mg) of fertiliser was added to the moistened soil and mixed by passing through a 2 mm sieve, four

times. The theory was that the fertiliser particles would stick to the moist soil aggregates preventing separation whilst being thoroughly mixed.

Samples (35 g) of the moistened fertilised soil (equivalent to 30 g air dry soil/fertiliser) were added to 75 ml pottles, 15 for each treatment. Another 7 ml of distilled water was added to each pottle and the cap lightly screwed on top, allowing gas exchange to prevent the development of anaerobic conditions but minimise soil moisture loss. Total MC of the soil in the pottles was 40.0 % w/w (32.7 % v/v; Table 3.2). The incubation temperature was 15^{o}C (close to the average temperature in the field in spring, where and when the field experiment was to be established).

Percent PR dissolution and changes in soil pH and Bic-P were measured on five sampling dates (SDs): 3 DAFA, 7 DAFA, 21 DAFA, 56 DAFA, and 155 DAFA. Each treatment by sample date (SD) combination was replicated three times.

Table 3.1. Treatment structure and nutrient (P and S) application rates used in the laboratory study. RPR is Ben Guerir RPR; BioS is BioSuper (a 5:1 blend of Ben Guerir RPR and elemental sulphur); BioP is BioPhos and TSP is triple superphosphate.

Treatment	P application rate (mg/kg soil)[a]	S application rate (mg/kg soil)
Control	0	-
RPR1	67	-
RPR2	133	-
RPR3	267	-
RPR4	533	-
RPR5	1333	-
BioS3	267	420
BioS5	1333	2100
BioP3	267	-
BioP5	1333	-
TSP3	267	-
TSP5	1333	-

[a] This is also equivalent to a field application rate (kg P/ha) assuming incorporation depth of 10 cm and soil bulk density of 1.0 g/ml.

3.3.2 SAMPLE PREPARATION AND ANALYSIS

At each SD the following analytical techniques were used to determine:

1. *Soil pH.* 14.0 g of moist soil (equivalent to 10 g air dried soil) was mixed with 21 ml distilled water (total soil: water ratio = 1: 2.5) and shaken for 30 minutes at

30 rpm in and end-over-end shaker and left over night (ca. 18 hours) to equilibrate. Soil pH was measured with a temperature-compensated saturated KCl reference-electrode.

2. *Bic-P.* 14.0 g of moist fertilised soil was shaken with 200 ml 0.5M $NaHCO_3$ for 30 minutes in an end-over-end shaker; then centrifuged at 3000 rpm for 10 minutes (Blakemore et al., 1987). Phosphorus content of the extractant was measured using the Heteropoly blue technique (Prokopy, 1993). Note Bic-P concentrations are expressed on a w/w basis (µg/g).

3. *PR dissolution*. 14.0 g of moist soil was mixed with 50 ml buffered $BaCl_2$-TEA (Bascomb, 1964), shaken for 1 hour in and end-over-end shaker, centrifuged at 3000 rpm for 10 minutes and filtered through Whatman No. 2 paper. The Ca concentration of the extractant was measured using ICP-OES (Hamalova et al., 1997). Calcium standards were made up in the same barium chloride matrix as the samples. Standards and samples were run using a primary wavelength of 396.847 nm and a secondary wavelength of 422.673 nm.

Note the estimation of PR dissolution is based on the assumption of congruent dissolution of P and Ca from the PR fertilisers (Hughes and Gilkes, 1984) and was calculated from the ratio of total P to total Ca in the fertiliser (Table 3.3).

3.3.3 DATA ANALYSIS

Data was analysed in Genstat V9 using analysis of variance (ANOVA) and regression. Probability levels were set to P=0.05. Where ANOVA indicated a significant result ($P<0.05$), means were separated by the least significant difference ($LSD_{0.05}$). Triple superphosphate was not included in any of the data analyses.

An exponential equation in the form of $y = -B(1-R^x)$ was fitted to the PR dissolution and Bic-P data over time; where y is the amount of P dissolved (either as a percentage of that applied or the absolute amount; mg P) or the Bic-P concentration (µg/g); x is the DAFA; B is the horizontal asymptote of the curve; and R is the curvature coefficient

describing the sharpness of the curve (0 < R < 1). Values of *R* close to unity (1) have a relatively gentle curve and gradually approach the value of *B*. Lower *R* values have a sharper bend as the curve rapidly approaches the value of *B*.

3.4 RESULTS

3.4.1 PHYSICAL AND CHEMICAL PROPERTIES OF THE SOIL AND FERTILISERS

The Bic-P concentration of the soil (22.0 µg/g) was higher than expected. Soil samples from the same paddock over the previous two years (unpublished) and during the field study (Chapter 4) were around 8 µg/g.

The reason Bic-P was higher than expected is probably a result of the method used to collect the soil and variability within the paddock. A total of ca. 20 litres of soil was collected from the paddock by the grower with a spade. It is likely that the soil sample was inadvertently collected from an area with abnormally high Bic-P. The field study (Chapter 4) showed that this paddock had two plots close to the paddock's only gate with Bic-P values of 30.6 µg/g and 19.6 µg/g. The mean Bic-P concentration of 43 other plots was 8.7 µg/g. Other fertility parameters of the soil (Table 3.2) were close to those of the field study.

Total porosity of the sieved soil was 46.2 % (v/v). Moisture content of the incubated soils was 32.7 % (v/v), so the degree of saturation was 86.5 % (v/v). The bulk of the soil (ca. 87 % w/w) was in the 250 µm to 2 mm size fraction.

Analysis of RPR (Table 3.3) indicated that the batch used in the present study had a similar total P content as that shown in the Ravensdown (2004) price schedule (13.5 % vs. 13.2 % w/w respectively). The Ca content was 30.1 %. About 67 % of the total P was soluble in 2 % formic acid, indicating that it is highly reactive (Bolland and Gilkes, 1997).

Specific surface area (m^2/kg) of each size particle fraction of the fertilisers was estimated based on the surface area to volume ratio of a sphere (Wang et al., 2005). A weighted mean diameter of each particle size fraction was used to estimate the number of particles in each size fraction, assuming mean aggregate density to be 3.0

g/ml (Hart et al., 2004). The estimated specific surface area of RPR (250 µm size fraction) was ca. 24.5 m^2/kg.

Table 3.2. Physical and chemical properties of the <2mm sieved soil fraction used in the laboratory study.

pH (1: 2.5 H_2O)	5.64
Bic-P (µg/g)	22.0
Cation exchange capacity (me/100g)	16
Calcium (me/100g)	6.3
Magnesium (me/100g)	2.44
Potassium (me/100g)	1.00
Sodium (me/100g)	0.15
Base saturation (%)	60.4
Sulphate-S (mg/kg)	9.0
P-retention (% w/w)	34
Organic-C (% w/w)	4.6
Total-P (%w/w)	0.098
Bulk density (g/ml)	0.82
Total porosity (% v/v)	46.2
Soil moisture content (% v/v)	32.7
Particle size distribution (% w/w)	
<45 µm	1.2
45-63 µm	2.5
63-125 µm	3.5
125-250 µm	5.9
250-500 µm	16.9
500-1000 µm	33.9
1000-2000 µm	36.1

Analysis of the <250 µm fraction of BioPhos indicated that the batch used in the present study had a much higher total P content (14.1 % w/w) than a similar product used in Ashcroft et al. (2004) (9.6 % w/w) suggesting that it was made from a different PR source. BioPhos currently manufactured and supplied by Ballance Agri-Nutrients Ltd is reported to have a total P concentration of 11.0 %. Removing the coarser material from the product (>250 µm; 26 % w/w) during sieving may have affected the P concentration (Rajan et al., 1992) although this is unlikely to be significant. About 52 % of the total P was soluble in 2 % formic acid, indicating that it has relatively low reactivity (compared with RPR) and therefore its efficacy for direct application may be

limited (Bolland and Gilkes, 1997). The estimated specific surface area of BioPhos was ca. 29.6 m^2/kg.

Table 3.3. Physical and chemical properties (% w/w) of the fertilisers used in the laboratory study. Formic acid solubility value is a percentage of total P.

	RPR	BioPhos	S^o	TSP
Total P content	13.5	14.1	0.0	20.5[a]
Total Ca content	30.1	37.0	0.0	16.0[a]
Total S content	-	-	99.9[a]	1.0[a]
2% Formic acid solubility	67.4	51.8	-	-
Particle size distribution				
<45 µm	0.5	1.9		
45-63 µm	0.8	2.6		
63-125 µm	11.0	21.4		
125-250 µm	87.7	74.2		

[a] Values from Ravensdown Ltd's (2004) price schedule.
- Not measured.

3.4.2 FERTILISER DISSOLUTION

As fertiliser application rate increased there was a decrease in percentage of total applied P that dissolved (Table 3.4 and Figure 3.1), and an increase in the absolute amount (µg) of P dissolved (Figure 3.2). Log transforming the data did not affect the significance of the results so raw data are presented. On the last three SDs (22, 57 and 155 DAFA) RPR1 had an average of 6 times greater variability than the other treatments. Kanabo and Gilkes (1988c) stated that the extractable Ca method may not be suitable for assessing PR dissolution at low PR application rates because of interference from exchangeable Ca already present in the soil, so this high variability may be an artefact of this method.

Excluding RPR1 from the analysis on the last two SDs increased the significance of the ANOVA on these SDs ($P = 0.027$ and $P < 0.001$ for 57 and 155 DAFA respectively; with respective $LSD_{0.05}$ values of 8.9 and 4.2 % for the percent dissolution data; Table 3.4). Within treatments the percent dissolution was generally greater on each successive SD. However, within SDs, percent dissolution tended to decrease as application rate increased. Dissolution of BioS3 was generally higher than BioP3 but not RPR3 during the first three SDs. BioS5 was not significantly different from BioP5 or RPR5 on any SD,

probably because at these rates the ability of the soil to buffer the solution Ca (and P) concentration may have been exceeded, limiting further dissolution (Robinson and Syers, 1991).

Table 3.4. Percentage dissolution of the PR-based fertilisers on each sample date. Treatment suffix numbers 1 to 5 relate to fertiliser application rate; 67, 133, 267, 533 and 1333 mg P/kg soil, respectively.

	DAFA				
Treatment	3	8	22	57[a]	155[b]
RPR1	11.2	41.5	51.4	60.6	75.5
RPR2	20.1	13.7	31.9	34.4	39.6
RPR3	10.1	9.7	23.0	27.5	43.2
RPR4	6.2	15.8	22.8	27.6	36.3
RPR5	5.9	10.6	16.6	21.4	26.6
BioP3	6.1	11.0	14.8	21.0	37.5
BioP5	4.3	11.4	12.6	17.4	23.6
BioS3	14.9	15.9	29.7	28.4	56.2
BioS5	7.7	11.0	15.9	24.0	32.0
F-pr	<0.001	<0.001	<0.001	0.043	0.084
LSD	5.2	6.9	9.7	23.4	32.3

[a] when RPR1 was excluded from the analysis P = 0.027 and LSD = 8.9
[b] when RPR1 was excluded from the analysis P <0.001 and LSD = 4.2

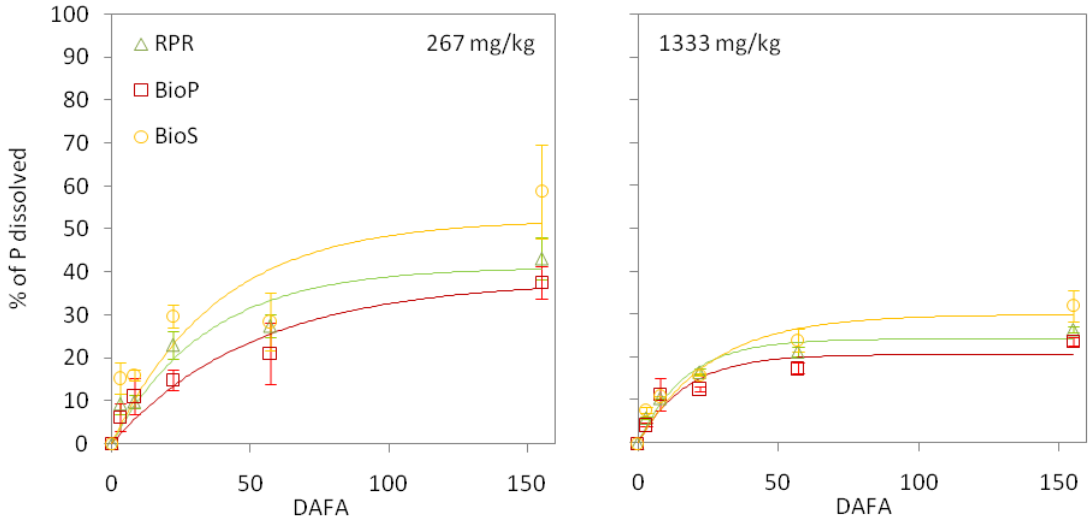


Figure 3.1. Changes in the amount P dissolved (as a percentage of that applied) over time (days after fertiliser application; DAFA) for RPR, BioPhos (BioP) and BioSuper (BioS) applied at two application rates (267 and 1333 mg P/kg soil). Error bars are $^{+}/_{-}$ the SEM for each sample date. Curves are fitted using Equation 3 (see text for details).

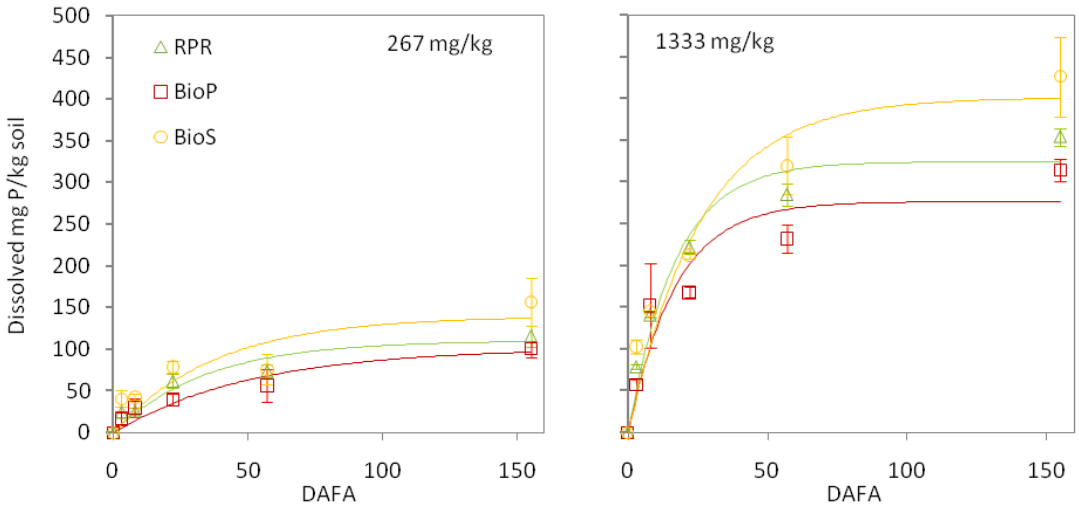


Figure 3.2. Changes in the amount of P dissolved (mg P/kg soil) over time (days after fertiliser application; DAFA) for RPR, BioPhos (BioP) and BioSuper (BioS) applied at two application rates (267 and 1333 mg P/kg soil). Error bars are $^{+}/_{-}$ the SEM for each sample date. Curves are fitted using Equation 3 (see text for details).

The changes in PR dissolution over time at the various application rates were modelled using:

Equation 3.

$$\Delta P = -B(1-R^{x})$$

Where ΔP = amount (percent or absolute) of P dissolved; B = the asymptote; R = curvature fitting parameter and x = DAFA.

The PR dissolution models (Figure 3.1 and Figure 3.2) were highly significant ($P<0.001$) and fitted the data well for most treatments except for RPR1, BioS3, RPR2 and BioP3 where the R^2 was 0.55, 0.69, 0.75 and 0.75 respectively (Table 3.5). All other treatments had R^2 values > 0.80. However, the curves in Figure 3.2 appear to flatten off excessively and too quickly at 1333 mg P/kg soil, where the data shows a more sustained period of dissolution than is described by this model.

Dissolution of TSP was not measured because dissolution of P and Ca is not congruent, as much of its P content is added during the manufacturing process. However it is assumed that nearly all of TSP would dissolve rapidly following application to a wetted soil (Kanabo and Gilkes, 1988c).

Table 3.5. Parameters for the exponential equation ($\Delta P = -B(1-R^x)$) describing the percent dissolution of RPR, BioPhos (BioP) and BioSuper (BioS) (ΔP) over time (x; days after fertiliser application) at different application rates (treatment suffix numbers; see Table 3.1)

	Parameter values		Standard errors		Significance	
Treatment	*R*	*B*	*R*	*B*	R^2	*F-pr*
RPR1	0.896	-62.6	0.066	9.4	0.55	<0.001
RPR2	0.907	-36.6	0.027	3.0	0.75	<0.001
RPR3	0.971	-41.1	0.007	3.5	0.87	<0.001
RPR4	0.938	-32.4	0.001	1.9	0.90	<0.001
RPR5	0.942	-24.4	0.006	0.9	0.96	<0.001
BioS3	0.974	-52.2	0.010	8.4	0.69	<0.001
BioS5	0.962	-30.1	0.008	2.1	0.88	<0.001
BioP3	0.981	-37.9	0.007	5.8	0.75	<0.001
BioP5	0.942	-20.7	0.015	1.6	0.83	<0.001

There was no significant relationship between *R* and application rate. Dissolution of BioSuper was more sustained and consistent over the (155 day) incubation period compared with RPR and BioPhos at equivalent application rates (Figure 3.1 and Figure 3.2).

The *B* parameter for percent dissolution tended to decrease with increasing application rate in all treatments. For RPR the relationship was $B = 11.08\ Ln(x)+101.3$ ($R^2 = 0.78$) where *x* is DAFA.

3.4.3 Changes in soil pH

There was an initial small (< 0.1 unit), insignificant rise in pH over the 0 to 3 DAFA period in all treatments (Table 3.6). Following this there was a rapid decrease in soil pH over the next two SDs, and then a slower but steady decrease in soil pH over the remaining SDs. There was much more variability associated with the Control than the other treatments at 3 and 8 DAFA (Figure 3.3), which may have affected the

significance of the results on these SDs. The reason for the excessively high variability in the Control on these two SDs is unknown.

The significant, consistent and relatively large drop in pH after the initial increase in the Control, RPR and BioPhos treatments is likely to be the result of nitrification (Larsen and Widdowson, 1968; Rajan and Edge, 1980). The greater decrease in soil pH witnessed in the BioS5 treatment is the combined result of S^o oxidation (Lee et al., 1987) and probably also nitrification (as mentioned above). BioS3 was expected to cause a drop in pH relative to RPR3 and BioP3 but it did not. It is probable that most of the protons released during the oxidation of S^o were neutralised by the enhanced dissolution reaction (Equation 1); recall that the percent dissolution (*B* parameter) was considerably greater in BioS3 than in RPR3 and BioP3.

Table 3.6. Changes in soil pH for RPR, BioPhos (BioP) and BioSuper (BioS) on each sample date. Treatment suffix numbers 1 to 5 relate to fertiliser application rate; 67, 133, 267, 533 and 1333 mg P/kg soil respectively. The Control had no P fertiliser added. pH at the start of the experiment was 5.64.

	Days after fertiliser application				
Treatment	3	8	22	57	155
Control	5.76	5.68	5.33	5.20	5.03
RPR1	5.74	5.52	5.32	5.23	5.01
RPR2	5.76	5.58	5.34	5.28	5.03
RPR3	5.83	5.59	5.37	5.30	5.04
RPR4	5.77	5.63	5.48	5.41	5.13
RPR5	5.86	5.73	5.58	5.58	5.29
BioP3	5.75	5.53	5.35	5.24	5.00
BioP5	5.75	5.62	5.46	5.40	5.17
BioS3	5.77	5.58	5.34	5.22	4.98
BioS5	5.75	5.66	5.37	5.01	4.78
F-pr	0.479	0.10	<0.001	<0.001	<0.001
LSD	0.12	0.14	0.05	0.05	0.10

Antimicrobial agents such as toluene are used in some studies to inhibit nitrifying bacteria and maintain a more stable soil pH (Kanabo and Gilkes, 1987b; Kanabo and Gilkes, 1988b), but these could not be used in the present study because the oxidation of S^o in BioSuper was relying on native, actively growing, soil micro-organisms (*Thiobacilli* spp.) (Lee et al., 1987).

By calculating the changes in soil pH over time relative to the Control, it is clear that there was a significant relative increase in soil pH in the RPR and BioPhos treatments (applied at 1333 mg P/kg soil) from SD3 (22 DAFA) onwards and a significant decrease in soil pH over the same period for BioSuper applied at the same rate (Figure 3.3). This was not so clear at 267 mg P/kg soil although there are indications of similar trends.

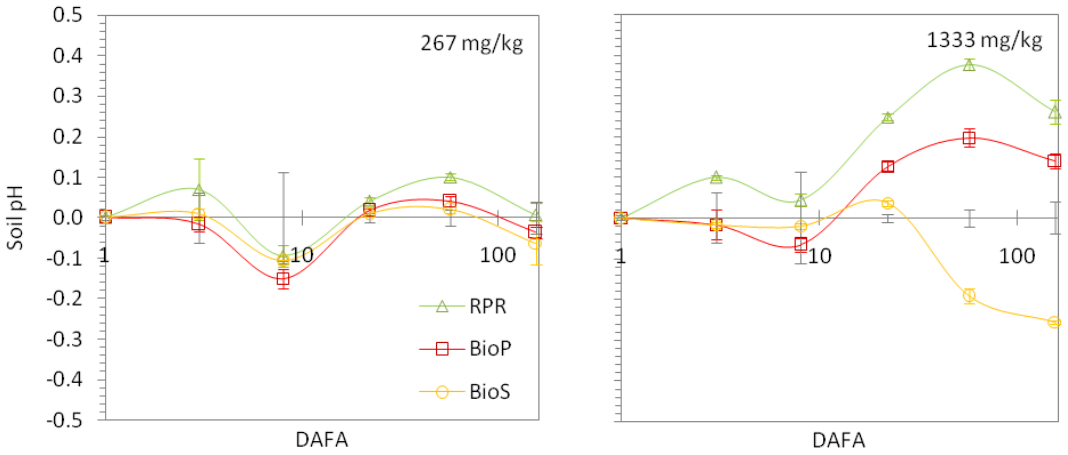


Figure 3.3. Changes in soil pH over time (days after fertiliser application, DAFA; note the log scale) for RPR, BioPhos (BioP) and BioSuper (BioS) at two application rates (267 and 1333 mg P/kg soil), relative to the Control (y-axis set to zero; error bars centred on the x-axis). Error bars are $^{+}/_{-}$ the SEM for each sample date. The Control had no P fertiliser added.

3.4.4 Changes in Bic-P

For a given fertiliser type, Bic-P generally increased with increasing application rate and on each successive SD (Table 3.7). Log transforming the data did not affect the significance of the results so analysis was done on the raw data.

There were significant differences among treatments on all SDs (Table 3.7). On each SD Bic-P concentrations in the RPR treatments were ranked RPR5 > RPR4 $\geq$ RPR3 $\geq$ RPR2 = RPR1. These trends were the result of absolute and relative differences in application rate. For instance, the relative difference in application rates between RPR5 and RPR4 was 2.5 times and the absolute difference between them was 800 mg P/kg soil;

whereas RPR4 was only two times that of RPR3 and the difference between them was 266 mg P/kg soil.

Comparing the different fertilisers at equivalent application rates (267 and 1333 mg P/kg soil), RPR was not significantly different from BioPhos on most SDs. BioSuper was significantly higher than RPR and BioPhos on SD4 and SD5 (57 and 155 DAFA respectively).

Treatment TSP3 increased Bic-P to 58.8 µg/g within 3 DAFA, followed by a slow but steady decline in Bic-P, probably the result of P-fixation; likewise TSP5 increased the soil Bic-P concentration to 280 µg/g with the same apparent trends (Table 3.7).

The relationship between the changes in Bic-P over time at various application rates for each fertiliser was modelled using:

Equation 4

$$\Delta Bic\text{-}P = -B(1-R^{x})$$

Where $\Delta Bic\text{-}P$ is the change in Bic-P relative to the Control; B is the asymptote of the curve; R is the curvature coefficient; and x is DAFA.

Table 3.7. Changes in Bic-P relative to the Control for each sample date. Treatment suffix numbers 1 to 5 relate to fertiliser application rate; 67, 133, 267, 533 and 1333 mg P/kg soil respectively. The Control had no P fertiliser added.

	Days after fertiliser application				
Treatment	3	8	22	57	155
RPR1	0.28	1.13	1.33	2.43	3.60
RPR2	0.50	1.33	1.93	3.83	3.60
RPR3	2.00	1.60	3.20	4.47	8.23
RPR4	1.17	3.20	5.40	9.13	11.43
RPR5	2.60	5.90	9.50	15.37	17.57
BioP3	0.33	0.90	1.50	3.33	7.10
BioP5	1.90	5.27	8.60	14.70	18.31
BioS3	-0.30	1.73	2.50	5.87	8.77
BioS5	2.13	5.43	9.97	19.13	27.83
TSP3[a]	58.8	55.7	55.9	57.8	50.1
TSP5[a]	279.9	263.7	246.8	260.9	215.1
F-pr	<0.001	<0.001	<0.001	<0.001	<0.001
LSD	0.65	0.57	1.37	1.76	2.75

[a] TSP data was not included in the ANOVA

The fitted curves at application rates of 267 and 1333 mg P/kg soil are shown in Figure 3.4. The model parameters for all treatments are shown in Table 3.8. The models were solved to calculate DAFA for 95 % of parameter *B* (X_B^{95}) at the estimated and upper and lower 95 % CI's of *R* (Table 3.8). Larger *R* values are more sensitive to small changes than lower values. Thus, *R* values of some treatments with apparently low SE have a large range between the upper and lower 95 % CI's (e.g. RPR3 and BioP3).

There was no clear relationship between X_B^{95} estimates and application rate, i.e. the length of time to 95 % of the estimated maximum change in Bic-P was not systematically affected by application rate. However, if only the 267 and 1333 mg P/kg soil rates are considered for a given fertiliser, higher rates appeared to correspond with a lower X_B^{95} estimate. Unfortunately we could not test the significance of this relationship because there were no replicates of the *B* parameters and X_B^{95} estimates. However, the fact that there was no overlap in the 95 % CI's between 267 and 1333 mg P/kg soil within RPR and BioPhos treatments indicate that the apparent differences might have been significant. The ∞ value for the upper 95 % CI for X_B^{95} for RPR1 and BioP3 in Table 3.8 were because the *R* value for this CI was >1.0. Values of R >1.0 produce a curve with a negative slope so a linear relationship (which would never reach an asymptote) was assumed, although this is clearly not possible given the finite amount of P applied.

The Bic-P models described the data well for all application rates and PR fertilisers. Predicted vs. observed R^2 = 0.99 with only a slight underestimation of the predictions (Figure 3.5). The change in Bic-P in response to the absolute amount of P dissolved from RPR was strongly linear (*y = 0.05x+0.2*; R^2 = 0.95) (Figure 3.6). Wright et al. (1992) also found a linear relationship between the change in Bic-P in response to the amount of P dissolved from North Carolina RPR. The relationship for BioPhos was also linear; *y = 0.15x – 3.2* (R^2 = 0.83), the steeper slope suggesting that with equivalent amounts of dissolved P BioPhos increases Bic-P more than RPR. The relationship for BioSuper (*y = 0.096x-1.6*) was much weaker (R^2 = 0.37).

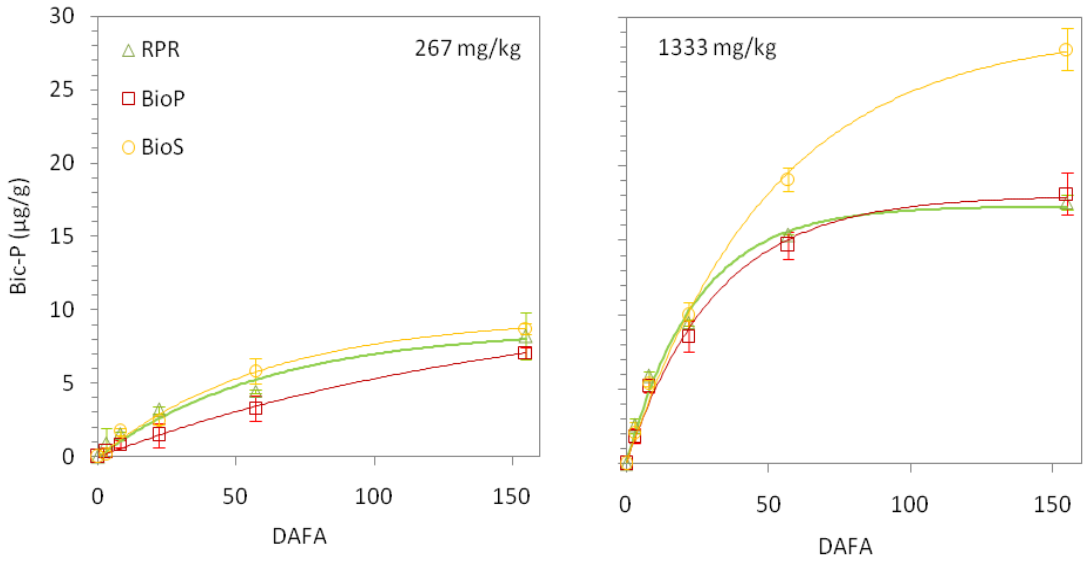


Figure 3.4. Changes in Bic-P over time (days after fertiliser application; DAFA) relative to the Control (set at zero) for RPR, BioPhos and BioSuper at two application rates (267 and 1333 mg P/kg soil). The Control had no P fertiliser added. Model parameters are presented in Table 3.8. Error bars are $^{+}/_{-}$ the SEM for each sample date. Curves are fitted using Equation 4 (see text for details).

Table 3.8. Parameters for the exponential equation ($\Delta Bic\text{-}P = -B(1-R^x)$) describing the changes in Bic-P (ΔBic-P; µg/g) over time at different fertiliser application rates. Note treatment suffix numbers 1 to 5 correspond with fertiliser application rates: 67, 133, 267, 533 and 1333 mg P/kg soil respectively. X_B^{95} is 95 % of the number of days after fertiliser application when *B* is reached.

	Parameter values		Standard errors		Significance		95 % CI	
Treatment	*R*	*B*	*R*	*B*	R^2	*F-pr*	X_B^{95}	Lower/upper
RPR1	0.977	-3.62	0.015	0.95	0.47	<0.001	132	50/∞
RPR2	0.958	-3.79	0.008	0.24	0.92	<0.001	70	50/116
RPR3	0.984	-8.74	0.006	1.37	0.81	<0.001	186	105/786
RPR4	0.969	-11.35	0.003	0.43	0.97	<0.001	96	78/124
RPR5	0.960	-17.31	0.003	0.43	0.99	<0.001	74	64/87
BioP3	0.994	-11.21	0.003	3.83	0.91	<0.001	467	220/∞
BioP5	0.969	-18.01	0.004	0.83	0.96	<0.001	94	74/129
BioS3	0.984	-9.52	0.003	0.71	0.96	<0.001	183	134/290
BioS5	0.981	-29.07	0.002	1.10	0.98	<0.001	153	128/190

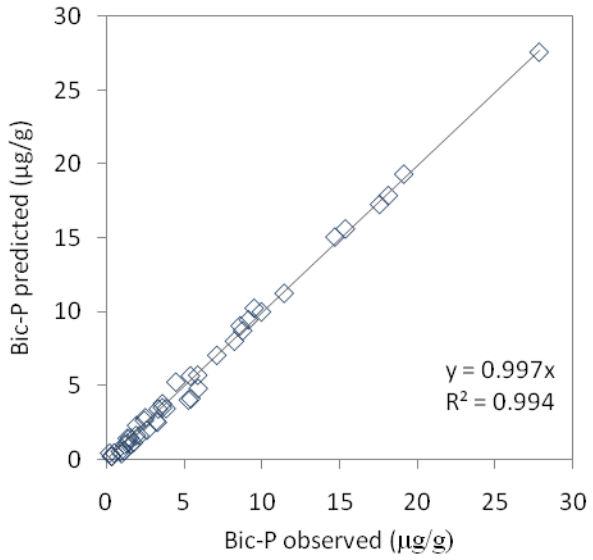


Figure 3.5. Fit of the model *ΔBic-P = -B(1-R^x)* describing changes in Bic-P (*ΔBic-P*) over time (*x*) for RPR, BioPhos and BioSuper.

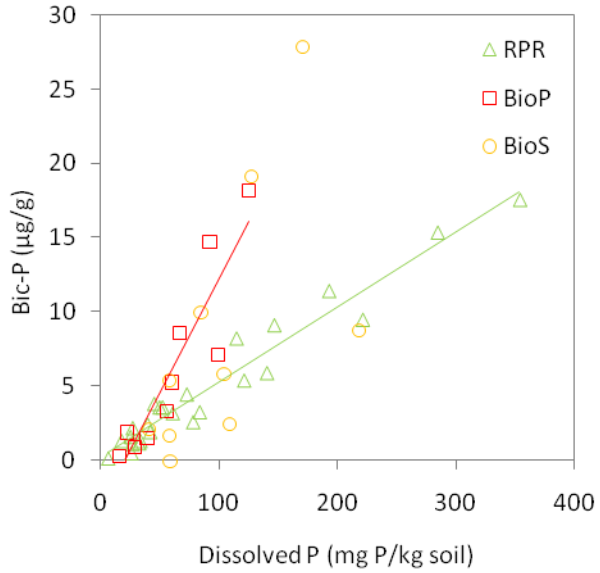


Figure 3.6. The relationship between Bic-P and P dissolved from RPR, BioPhos (BioP) and BioSuper (BioS). The linear regression lines were significant for RPR (*y = 0.05x+0.2*; R^2 = 0.95) and BioP (*y = 0.153x-3.2*; R^2 = 0.83) but not BioS (*y=0.096x-1.6; R^2=0.37*).

3.5 Discussion

The dissolution and changes in Bic-P over time for BioPhos were similar to RPR which was surprising given that RPR was much more soluble (reactive) than BioPhos in 2 %

formic acid (Table 3.3) (Bolland and Gilkes, 1997). One of the differences between BioPhos and RPR was that BioPhos was markedly finer than RPR, with BioPhos having an estimated specific surface area about 17 % greater than RPR. However, the reactivity test should theoretically have accounted for differences in particle size (see section 2.2.1), so the reason that BioPhos dissolved equally fast as RPR despite BioPhos having markedly lower reactivity is possibly related to the microbial beneficiation (see section 2.3.1). It seems likely that if a more reactive source of PR was used to manufacture BioPhos then there may be a significant agronomic advantage over Ben Guerir PR.

Dissolution of the fertilisers and subsequent changes in Bic-P followed expected trends (Khasawneh and Doll, 1978; Rajan and Edge, 1980; Rajan et al., 1991a; Hedley and Bolan, 1997). Kanabo and Gilkes (1988c) undertook a study similar to this one using North Carolina PR with strikingly similar results. Although their data were presented as a function of application rate, here it was presented in relation to incubation period (DAFA). Furthermore, the modified Genstat models (Equation 4) presented here are very similar to the Mitscherlich function $y = A(1 – e^{(–cx)})$ used by Kanabo and Gilkes (1988c). To get the Mitscherlich parameter values from the GenStat equation, the conversions are $A = –B$ and $C = –ln(R)$.

There was no significant relationship between *R* parameter values and application rate in the Bic-P models for the RPR treatments (Table 3.8). However, *B* parameter values were correlated with application rate and appeared to differ among some treatments (Figure 3.7). Unfortunately, the significance of these differences for the BioPhos and BioSuper treatments could not be tested because there was not enough data available. For RPR this was a Log-normal relationship ($R^2 = 0.87$). BioPhos data fitted reasonably well onto the RPR curve so a single model was used to describe the changes in parameter *B* and application rate for these treatments ($R^2 = 0.93$; Figure 3.7). Furthermore, these treatments were similar on all SDs at both the 267 and 1333 mg P/kg soil application rates (Table 3.7), which suggested that these two treatments could be pooled and a single model used to describe changes in Bic-P over time.

BioSuper data also fitted well onto the RPR curve at 267 mg P/kg soil, but not at 1333 mg P/kg soil. This could be expected because at the lower application rate (267 mg P/kg soil) these two treatments behaved similarly over the 155 day incubation period but at 1333 mg P/kg soil changes in Bic-P were significantly higher for BioPhos than RPR on the last two SDs (Table 3.7). Linear regression (application rate vs. *B* parameter including the ≤267 mg P/kg soil RPR data and the BioSuper (267 and 1333 mg P/kg soil) data produced an R^2 of 0.99, although the highest rate of BioSuper did have a great amount of leverage on the regression (Figure 3.7). Note these relationships between *B* and application rate were to be used to integrate the laboratory and field studies (Chapter 5).

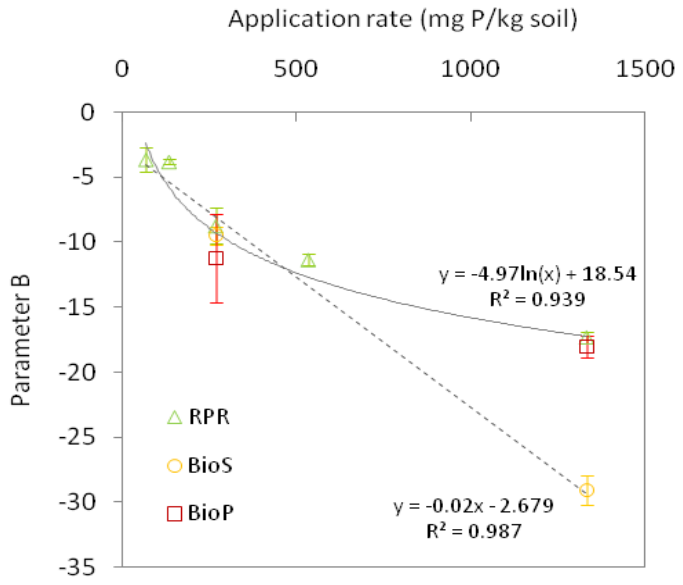


Figure 3.7. The relationship between fertiliser P application rate and *B* (asymptote) parameter values for the equation $y = -B(1-R^x)$ describing the changes in Bic-P (*y*) over time (*x*) for various P application rates. Error bars are $^+/_-$ the standard error of the treatment means for each application rate. The Log-normal (solid) curve was fitted through the RPR and BioP data at all application rates; whereas the linear regression (dashed) line was fitted through the BioS data and the three lowest application rates of RPR (67, 133 and 267 mg P/kg soil; see text above for the rational used to justify this approach).

Dissolution of field applied PR tends to occur at a slower rate than that applied in incubation studies. Robinson et al. (1994) suggested that the amount of dissolution that occurs in laboratory experiments conducted in near optimal conditions in about 60

days is what could be expected to occur in the field in a year. Because this was the only information found in the literature comparing differences in PR dissolution rate between laboratory and field studies this relationship (although clearly having its limitations) was used to estimate the amount of P dissolution that might occur in the field study at the various application rates used in the (present) laboratory study.

When taken as a temporally independent percentage (i.e. 60/365 = 0.16), this relationship suggests that dissolution in the field would occur at a rate of approximately 16 % of that which occurs in the laboratory. Because the change in Bic-P as a result of PR dissolution in the present study is linear (Figure 3.6); Bic-P data were simply multiplied by 0.16 to estimate ball-park changes in Bic-P that might occur in the field at various application rates and contact periods. Adjusted data for RPR3, BioP3, BioS3, and RPR5, BioP5 and BioS5 are shown in Figure 3.8.

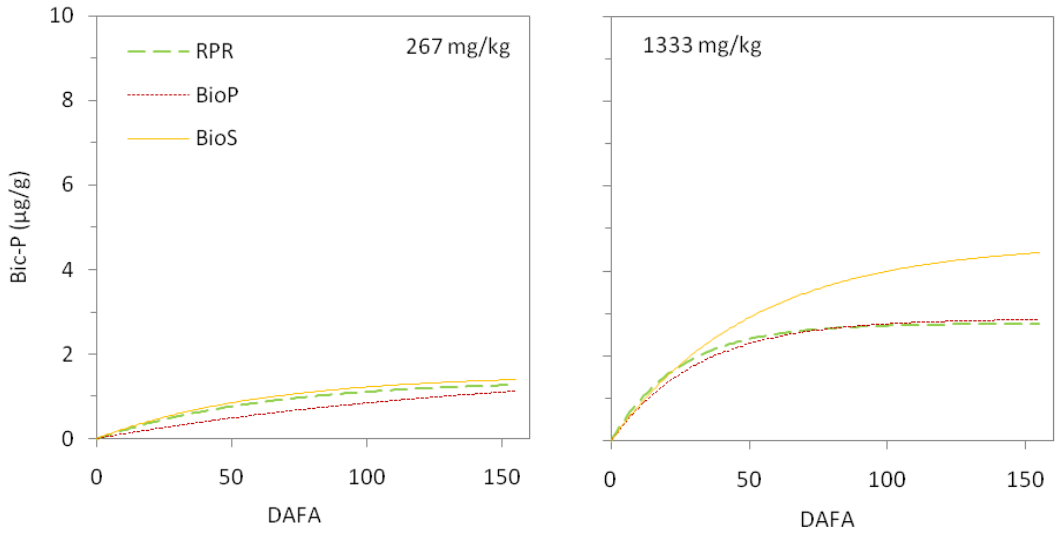


Figure 3.8. Expected changes in Bic-P over time (DAFA; days after fertiliser application) for various rates of RPR, BioPhos (BioP) and BioSuper (BioS) under field conditions. Data are from Figure 3.4 adjusted for a 16 % comparative dissolution rate between field and laboratory experiments (Robinson et al., 1994). Note data for BioP and BioS are purely speculative as there have been no apparent studies on the comparative dissolution between field and laboratory experiments for these fertilisers.

Adjusted data indicate that by 155 DAFA changes in Bic-P for RPR and BioPhos applied at ca. 1333 mg P/kg soil (2.7 µg/g) are likely to be around twice that of 267 mg P/kg soil

(1.1 µg/g). For BioSuper applied at 1333 mg P/kg soil (BioS5; ca. 4.2 µg/g) the changes might be around three times greater than at 267 mg P/kg soil (BioS3; 1.2 µg/g). The shape of the curves suggests that the comparative differences between these two application rates are greater early on. For RPR and BioPhos the higher rate plateaus higher and earlier than the lower rate.

These results indicated that the best rates to use in the field study would be a top rate as high as practical and within the bounds of the rates tested here (i.e. $\leq$ 1,333 mg P/kg soil) with the lowest rate somewhere around 250 mg P/kg soil (because below this only very small changes in Bic-P could be expected).

Fertiliser dissolution was not measured in the field because of the difficulties accounting for P losses (see section 2.2.7). Furthermore, because of the significant drop in pH expected in the BioSuper treatment in the field study, a crop tolerant of low soil pH must be used. Potatoes were thought to be an ideal test crop for the field experiment because they are a crop of interest for the local growers, they are reasonably tolerant of low soil pH, they are a P-responsive crop, and because there have been no apparent published studies on the response of potatoes to PR fertilisers.

To determine whether or not a yield response could be expected if potatoes were planted soon after PR fertiliser application the nutrient response model PARJIB (Reid, 2002) was used to generate a P response curve using the relevant soil data from Table 3.2, with soil mineral N set at 84 kg N/ha (see section 4.4.1.1) and potential yield at 60 t/ha (thought to be a realistic, achievable yield) (Figure 3.9). This indicated that a significant yield response might occur even with small changes in Bic-P providing that initial soil Bic-P concentrations are low (< 10 µg/g). A shift of 5 Bic-P units (e.g. -*B* x *0.16*; of BioSuper at 1333 mg P/kg soil) from 9 to 14 µg/g should increase tuber yield by around 4 t/ha. However, given that the increase in Bic-P is not immediate (i.e. asymptote of Bic-P curves at high application rates were still not reached at 155 DAFA) it was recognised that the expected increases in yield that might occur in response to PR application would probably be small and may not be statistically detectable (significant). Nevertheless, because there have been a number of studies undertaken

showing enhanced P uptake and yield responses to PR from crops sown soon after PR application (Nagaraja et al., 1997; Evans et al., 2006), along with the fact that there have been no studies undertaken using potatoes as a test crop following application of Ben Guerir RPR, BioPhos or BioSuper (based on Ben Guerir RPR), justifies the undertaking of such a field experiment.

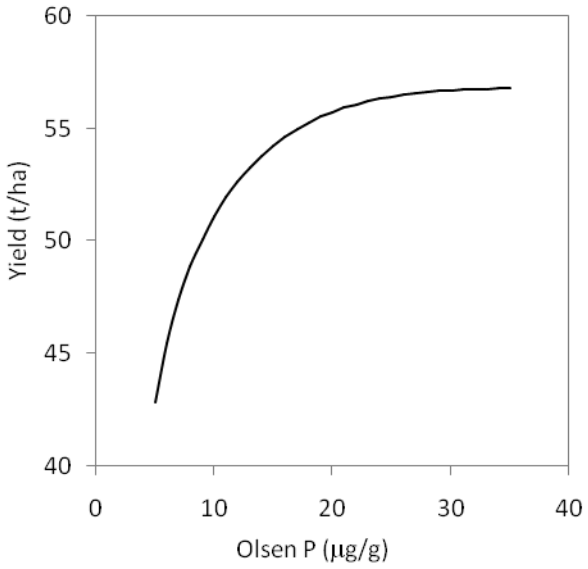


Figure 3.9. Yield response of potato to different Olsen P concentrations. Data generated using the PARJIB fertiliser response model (Reid, 2002). Potential yield was set at 60 t/ha and the relevant soil fertility parameters used from Table 3.2.

3.6 CONCLUSIONS

Dissolution of the PR fertilisers and subsequent changes in Bic-P over time at different application rates followed expected trends. Higher application rates decreased the relative proportion of total P that dissolved from the PRs but increased the absolute amount dissolved and the ΔBic-P over lower application rates. Phosphate rock dissolution and changes in Bic-P over time under laboratory conditions were accurately described by the exponential equation $y = -B(1-R^x)$ where x is DAFA. However, PR dissolution in field conditions occurs at a much slower rate than that which occurs in

the laboratory (Robinson et al., 1994) so these models will require calibrating for field conditions.

The dissolution rate and subsequent changes in Bic-P of BioPhos were virtually identical to RPR at equivalent application rates. This was surprising given that the reactivity was much lower in BioPhos than RPR (Table 3.3). The microbial beneficiation of BioPhos appears to have enhanced its ability to dissolve once applied to the soil. BioSuper had the fastest dissolution rate and the highest increases in Bic-P for a given P application rate.

The relationship between ΔBic-P and the amount P released from RPR was linear over the range of application rates tested ($y = 0.051x$; $R^2 = 0.95$). The changes in Bic-P in relation to the amount of P released from BioPhos ($y = 0.15x – 3.2$; $R^2 = 0.83$) were greater than they were for RPR, and the relationship for BioSuper was weak ($R^2 = 0.37$). The reason for the differences among treatments is unclear and more work needs to be done to understand why this occurred.

Because the changes in Bic-P in the field are expected to be much lower than in the laboratory study, coupled with the facts that the expected changes in Bic-P will be relatively small compared with water-soluble P_i fertilisers, higher at higher application rates, and delayed; this means that treatments with both high and low application rates will be needed if crop responses are to be achieved and/or differences among treatments in ΔBic-P or crop yield detected. Furthermore, due to the high initial P demand of most annual crops (including potato), whether or not a crop response will occur is uncertain even if the highest application rate used in this study (1333 mg P/kg soil) is utilised in the field.

CHAPTER 4

4 FIELD STUDY

4.1 OVERVIEW

A field study was undertaken to determine the yield response of potatoes to PR fertilisers applied using two application methods (broadcast and banded) and to provide field data on the changes in soil pH, Bic-P over time as a result of PR fertiliser application on an alluvial soil in Eastland's Waiapu valley, similar to that used by a number of ECOPT growers.

A split plot, complete randomised block design experiment was used. Fertilisers (RPR, BioPhos and BioSuper) were applied on 6 October 2004 either banded (20 cm wide bands at 85 cm centres) or broadcast (main plots); both incorporated to ca. 9 cm depth. A Control (no fertiliser) was included in the broadcast plots. Fertilisers (subplots) were applied at 115 kg P/ha in the banding plots and 488 kg P/ha in the broadcast plots resulting in soil fertiliser-P concentrations SFP of 678 mg P/kg soil for both treatments. Additional rates of RPR (40 and 250 kg P/ha; 236 and 1475 mg P/kg soil) were included in the banding plots. Soil samples for determination of soil pH and Bic-P fluxes were collected from the broadcast plots only at various intervals up to 344 DAFA.

Potato (cv. Desiree) was the test crop. This was planted 14 DAFA (20 October 2004) and harvested on 22 February 2005 at which time tubers were scored for incidence and severity of common scab (*Streptomyces* spp.) and separated into various size classes and the yield of each determined. Visual assessments and data indicated that the crop suffered from N deficiency and moisture stress, particularly over the later part of the season. The Potato Calculator (Jamieson et al., 2006) estimated the resulting yield reduction at ca. 50 %.

Phosphorus content of the shoots 43 days after planting in the broadcast plots was ranked BioSuper (0.42 %) > RPR (0.36 %) = BioPhos (0.36 %) > Control (0.33 %), but at

88 days after planting and at final harvest there were no differences among treatments in P content of the shoots and tubers respectively. There were no significant differences among any treatments in total tuber yield, although tuber yield and number (m^{-2}) in the largest size class (7.5 to 10 cm) was greatest in the Control (6.8 t/ha and 1.9 m^{-2} respectively) and lowest in broadcast RPR (0.5 t/ha and 0.2 m^{-2}). There were other significant differences among treatments in the tuber yield and tuber number of the largest size class, but these results were probably confounded by variability in soil mineralisable N and water availability indicated by significant although weak relationships between these (yield limiting) variables and tuber yield.

There were no significant differences in soil pH among the Control and the broadcast-RPR and BioPhos treatments on any SD, whereas BioSuper had significantly lower soil pH than the Control, RPR and BioPhos treatments on the last three SDs (57, 132 and 344 DAFA); probably the result of oxidation of the S^o included in BioSuper.

Increases in Bic-P over time were greatest in BioSuper, which had significantly higher Bic-P than RPR and BioPhos on the last two SDs. Differences between RPR and BioPhos were not significant on any SD. However, BioPhos was significantly higher than the Control on the last two SDs.

The increases in Bic-P fitted the same equation as in the laboratory study: $\Delta Bic\text{-}P = -B(1-R^x)$; where x is the number of days after fertiliser application. The ΔBic-P over time for RPR and BioPhos was similar so a single model was used to describe them both. The B parameter for RPR and BioPhos was -3.47 ($^+/_-$ 0.986) for and BioSuper -13.25 ($^+/_-$ 4.007). Respective R parameters were 0.993 ($^+/_-$ 0.005) and 0.995 ($^+/_-$ 0.003).

4.2 OBJECTIVES

The objectives of this study were to determine the yield response of potatoes to RPR, BioPhos and BioSuper applied using two application methods (broadcast and banded) and planted soon after fertiliser application, as well as the changes in soil pH and Bic-P imparted by these fertiliser treatments under field conditions.

4.3 METHODOLOGY

4.3.1 SITE

The experimental site was located on a north-facing intermediate river terrace of the Waiapu river near Tikapa (178°26'E, 37°49'S; Figure 1.1), approximately 15 km North East of Ruatoria, Eastland, New Zealand. The soil was a Hikuwai fine sandy loam (Rijkse, 1980).

The paddock had been used for growing kumara (*Ipomoea batatas* L.) over the previous three summer seasons, and left fallow over each winter. There had been no applications of fertiliser or manure since the grower had taken over the farm some 5 years earlier; and probably none (according to the grower) for the previous 20 or 30 years.

Mean monthly rainfall from Tikapa's closest long-term weather station (Hick's Bay; Figure 1.1) is shown in Figure 4.1.

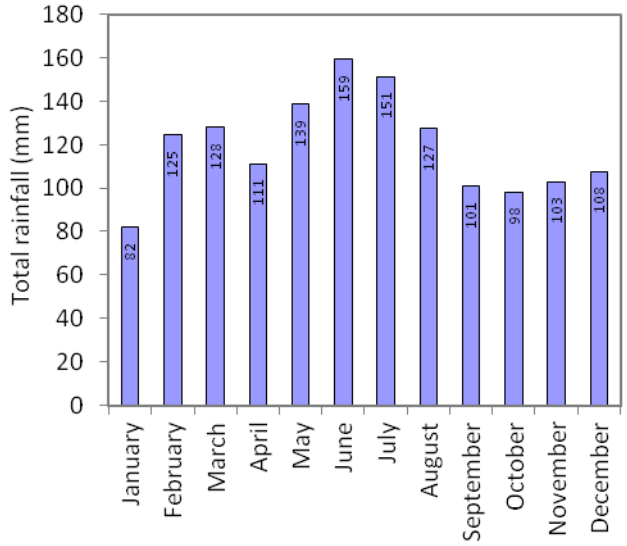


Figure 4.1. Mean monthly rainfall (15 years of data; 1991 to 2006) for Hicks Bay, approximately 25 km NNW of the field experiment site. Data courtesy of MetService (www.metservice.co.nz).

4.3.2 EXPERIMENTAL

Plots were marked out and fertiliser treatments applied on 6 October 2004. A split plot, complete randomised block design experiment with 5 replicates was used.

Two fertiliser application strategies (banding and broadcast) were the main plots; fertiliser type and rates were the subplots. Details of the treatments are outlined in Table 4.1. Subplots measured 6 m long by 3.4 m wide, with a 1 m buffer between the ends of each subplot to prevent contamination of applied fertiliser between plots. All fertilisers were passed through a 250 µm sieve prior to application.

Broadcast plots included a Control (no fertiliser) and three PR treatments: Ben Guerir RPR, BioSuper (a 5:1 blend of Ben Guerir RPR + S^o) and BioPhos; applied at a rate of 488 kg P/ha. These were incorporated using a tractor-mounted rotary hoe, to an average depth of 90 mm, giving an approximate soil fertiliser-P (SFP) concentration of ca. 542 mg P/l soil. The bulk density of the cultivated soil was ca. 0.80 g/ml so the density adjusted SFP concentration was ca. 678 mg P/kg soil.

The banding plots included the same fertilisers at the same bulk density adjusted SFP concentrations but these were applied and incorporated in 20 cm wide bands at 85 cm (centre to centre) spacing to an average depth of ca. 90 mm using a modified hand-operated rotary hoe; the field application rate was 115 kg P/ha. Two additional banded RPR treatments were also applied at bulk density adjusted SFP concentrations of 236 and 1476 mg P/kg soil (40 and 250 kg P/ha respectively).[7]

[7] Note bulk density of 1.0 and an incorporation depth of 10cm was used to calculate the SFPs prior to application and soil testing, which gave intended SFP concentrations that fell within the bounds of the laboratory application rates (i.e. 250 kg P/ha was intended to be 1062 mg P/kg soil).

Table 4.1. Treatment structure and nutrient application rates for the field study. Experiment was a split plot design with 5 replicates. All treatments were incorporated to a depth of about 8 -10 cm using a rotary hoe. Test crop used was potato (cv. Desiree). [SFP] = approximate (bulk density adjusted) soil fertiliser-P concentration.

Main Plot	Subplot	Fertiliser rate (kg/ha)	P rate (kg P/ha)	[SFP] (mg P/kg soil)	S rate (kg S/ha)	N rate[a] (kg N/ha)
Broadcast	Control	0	0	0	0	0
	BioS	3600	488	678	720	0
	BioP	3470	488	678	0	70
	RPR	3600	488	678	0	0
Banded	BioS	850	115	678	170	0
	BioP	820	115	678	0	16
	RPR1	360	40	236	0	0
	RPR2	850	115	678	0	0
	RPR3	1840	250	1475	0	0

[a] Organic N included in the product(s).

4.3.3 SOIL SAMPLING

Unforeseen difficulties keeping the rotary hoe in a straight line when incorporating the banded fertilisers were thought to have affected the dilution of the fertilisers with the soil, so the post-fertiliser-application soil sampling strategy was changed. The initial intention was to sample only from the fertiliser incorporation zone (planting row) of the banding and Control plots because this would include the full range of SFP concentrations on which to base the results, and which would help validate some later assumptions (see section 5.1). But instead only the broadcast plots were sampled, which were thought to have much more consistent fertiliser-soil mixing.

The soil sampling regime is outlined below. Soil analyses and subsequent calculations were performed using the methods outlined in section 3.3.2.

> On 8 October 2004, immediately prior to application of the fertiliser treatments, soil samples (0-15 cm; n = 10) were collected from each subplot to measure baseline values of: anaerobic mineralisable nitrogen; Bic-P (air dried); pH (air dried, 1:2.5 H_20). Note these measurements were to be used as covariates during data analysis.

Additional samples (0-15 cm and 15-30 cm; n = 18 for each depth) were collected on 8 October 2004 from each replicate for measures of: Olsen P; exchangeable cations and cation exchange capacity; P retention; organic carbon; sulphate-S.

On 19 October 2004, 2 December 2004, 16 February 2005 and 16 September 2005, each broadcast subplot (which included the Control) had samples (0-7.5 cm; n = 12) collected to measure: Bic-P (air dried); pH (air dried; 1:2.5 H_2O); soil MC (%).

Note the 7.5 cm deep cores were used because these sampled from within the fertiliser incorporation zone (note great care was taken to ensure that only the soil from the fertiliser incorporation zone was sampled); 15 cm cores would have included soil below the incorporation zone. Thus there was a compromise between the standard soil sampling depth of 15 cm (on which most fertiliser recommendations etc are based) and simplifying the analysis. If 15 cm cores were taken comparisons with the laboratory study would have been affected.

4.3.4 CROP MANAGEMENT

Potatoes (*Solanum tuberosum* cv. Desiree) were planted on 20 October 2004 using a 2-row (85 cm spacing) tractor-mounted planter. There were 4 rows planted per plot. Seed was sorted into two size classes before planting, 60-90 g, and the remainder (<60 g and >90 g). The two central rows (from which plants were to be harvested and soil samples collected) of each plot were sown with the 60-90 g seed, guard rows were planted with the remainder. This was done to minimise variability in the harvest rows caused by different sized seed potatoes.

Seed potatoes were sown within the incorporation zone of the fertilisers (2-8 cm beneath the surface) with soil mounded over the top. Mounding was performed in two stages, on 15 November 2004 and 2 December 2004. Weeds were controlled via mounding and hand weeding. No irrigation was applied.

Due to signs and evidence of nitrogen deficiency (Figure 4.2) Wuxal Amino liquid fertiliser (9.2 % N w/v) was applied. This was done after extensive collaboration with Bio-Gro and a technical advisor from the Wuxall distributor,[8] as well as a small trial on a separate crop of Desiree in Hastings aimed at determining maximum possible application rates while avoiding crop damage (data not shown). Wuxal Amino was applied directly to the soil on 17 January 2005, at 92 l/ha (10 kg N/ha) diluted to 1500 l/ha with H_2O, banded either side of each mound using a knapsack sprayer. This was supplemented by foliar application at label rates (5 l/ha diluted to 400 l/ha with H_2O; 0.5 kg N/ha). There was no appreciable damage to the crop during subsequent monitoring from either the soil or foliar applied applications.

Figure 4.2. The crop on 17 January 2005 immediately after application of Wuxall Amino. Note the severe N deficiency symptoms and wetted bands on the soil where Wuxall was applied (see text for details).

[8] Gavin Subritzky, Horticentre, http://www.horticentre.co.nz

Three temperature data loggers (Tiny Tag, model: TGX-3520; www.geminidataloggers.com) were also set up at the start of the experiment to measure soil temperature in the fertiliser incorporation zone over the course of the experiment.

4.3.5 CROP MEASUREMENTS

Plant tissue samples (8 whole stems per subplot) were collected from each subplot on 2 December 2004 and 17 January 2005. Samples were oven dried at 60^{o}C for two days and were later analysed for total P concentration using microwave digestion using nitric and hydrochloric acids and hydrogen peroxide and subsequent quantification with ICP-OES (Cunniff, 1999).[9]

Nitrogen deficiency symptoms were apparent from early December onwards. Symptoms were variable over the experimental area (probably because of variation in soil mineralisable N). In response to this additional plant tissue samples were taken from four randomly selected apparently N-deficient (yellow) and N-sufficient (dark green) plants on 6 January 2005 which were analysed for total N and P using ICP-OES (Cunniff, 1999).

Crop radiation interception was measured on 2 December 2004 and 6 January 2005 using a 'SunScan Canopy Analysis System' (Model SS1; Delta T devices; Cambridge, England); 6 readings (diagonally across the row) per plot were taken on each SD. Leaf area index was estimated using the relationship LAI = FRI x 4.5 where LAI = leaf area index, FRI = fraction of radiation intercepted (Stone et al., 1999).

Final harvest was undertaken on 22 February 2005. Two 4 m lengths of row (taken from the central 2 rows of the plots) were harvested. Plants were counted and the shoot material was collected, weighed, subsampled, re-weighed then oven dried at 65^{o}C for one week then at 80^{o}C for a further five days (because the fruitlets were not

[9] Personal communication with Peter Lorentz; technical and business development manager, Analytical Research Laboratories (www.ravensdown.co.nz/Services/ARL).

dry) until a constant mass was attained. A subsample was retained for P analysis using ICP-OES (Cunniff, 1999) as outlined above.

Potato tubers were dug by hand with spades. Tubers from each plot were weighed and split into size classes <2.5, 2.5-5.0, 5.0-7.5, 7.5-10.0 cm maximum diameter, which were weighed separately. A representative subsample of tubers was collected for DM analysis. These were chopped, weighed, and then oven dried at 80^{o}C until a constant mass was attained. A subsample of dried tuber material was retained for P analysis using ICP-OES (Cunniff, 1999). Disease assessments were also made on the tubers before the subsamples were collected. The only disease that was positively identified was common scab (*Streptomyces* spp.), and both the severity (average % of surface area affected with pustules) and incidence (% of tubers affected pustules) of this disease were recorded.

All shoot and tuber (ICP-OES) P content samples were kept in a cool store before analysis. These were retrieved for final preparation (grinding) and P analysis in December 2005. However the shoot samples from the final harvest (22 February 2005) were wet and severely infected with mould so were discarded which meant that total P-uptake of the crop at final harvest could not be assessed.

4.3.6 CLIMATE MEASUREMENTS

Air and soil temperature (2.5 m and 10 cm above and below ground respectively), solar radiation, rainfall, humidity, barometric pressure and wind speed were measured with a 'Weatherpro-plus' meteorological-station (www.scottech.net) situated about 70 m from the centre of the experimental area in an open (pasture) paddock.

A base temperature of 7^{o}C was used to calculate the thermal time in growing degree days (GDD; Sands et al., 1979).

4.3.7 DATA ANALYSIS

Data were analysed in Genstat V9 using ANOVA and regression functions. Probability levels were set to P = 0.05. Where ANOVA indicated a significant result (P<0.05), means

were separated using the least significant difference. In some cases results are discussed at the lower ($P<0.1$) probability level, mainly because of the difficulties and consequences associated with uncontrolled (experimental) variability; although this has been kept to a minimum.

Regression models of the changes in Bic-P over time (Equation 4) used all data points. The decision to use the same model as the laboratory study was based on the intention to use the field generated model(s) to calibrate the laboratory generated model(s), as well as the significance of the fit to the data ($P<0.001$).

4.4 RESULTS

4.4.1 ENVIRONMENT

4.4.1.1 SOIL

In most cases the soil fertility parameters (Table 4.2) were similar to those found in the laboratory experiment (Table 3.2). As alluded to in Chapter 3 the main exception to this was Bic-P, which was markedly lower in this (field) study (9.5 µg/g) than the laboratory study (22 µg/g). Soil pH was 5.6, comfortably below the PR application threshold of 5.8 considered the maximum pH value suitable for directly applied PR (Hedley and Bolan, 1997).

Differences in base saturation values (me/100 g) between the two studies were small (≤ 13 %). Total P was not measured in this study but was 0.098 % w/w in the laboratory experiment. Given that the Bic-P value was considerably higher in the laboratory study it is likely that the average total P in this study would be <0.098 % w/w.

Analysis of the soil aggregate size distribution (Figure 4.3) indicated that about 36 % of the mass of aggregates were <2 mm diameter. However, 100 % of the aggregates in the laboratory study were <2 mm diameter suggesting a much lower specific surface area (m^2/kg) in the field study.[10] Mean weight diameter of the soil in the fertiliser

[10] Differences between the laboratory and field studies in soil surface area and the effects this may have had on PR dissolution are discussed in section 5.4.2.

incorporation zone was 3.5 mm. See Table 3.3 and section 3.4.1 for details on the particle size distribution of the fertilisers.

Soil mineralisable N was variable among plots, ranging from 47 to 143 kg N/ha; Table 4.2) and reasonably high (mean = 84 kg N/ha; Table 4.2) considering the length of time the land had been used for growing crops without the use of fertilisers, composts or green manures.

Table 4.2. Soil fertility parameters for the 0-15 and 15-30 cm depth increments. n = 9, except for ^ in which case n = 45.

		0-15 cm		15-30 cm	
	Units	Mean	SEM	Mean	SEM
pH	Log[H^+]	5.6^	0.02^	5.4	0.08
Mineralisable N	kg N/ha	84^	4.1^	-	-
Bic-P	µg/l	9.5^	0.59^	7.8	1.19
Sulphate S	µg/g	4.8	0.22	-	-
P retention	% w/w	34.0	0.79	-	-
Organic matter	% w/w	5.0	0.12	-	-
Bulk density	g/ml	0.8	0.01	-	-
CEC	me/100g	12.6	0.27	12.2	0.55
Ca	me/100g	4.8	0.20	4.4	0.29
Mg	me/100g	1.6	0.11	1.7	0.10
K	me/100g	0.9	0.06	0.5	0.05
Na	me/100g	0.1	0.01	0.1	0.00
Base saturation					
Ca	%	38.6	1.52	36.0	1.52
Mg	%	13.0	0.81	14.1	0.55
K	%	6.8	0.42	4.1	0.35
Na	%	1.0	0.04	1.1	0.05
Total	%	59.4	2.13	55.3	1.78

Note; there were two adjacent plots closest to the paddock gate with abnormally higher Bic-P concentrations (30.6 and 19.7 µg/g) in the 0-15 cm depth increment (the third highest value was 13.2 µg/g). If these two highest values are excluded the mean Bic-P concentration is 8.7 µg/l (SEM = 0.24).

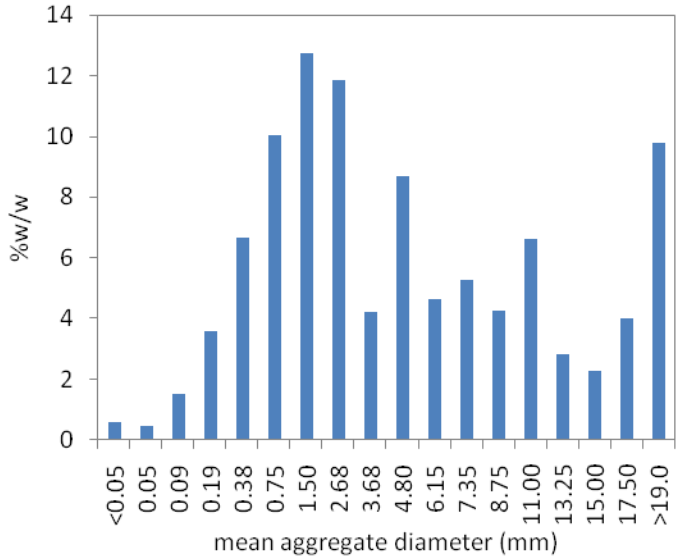


Figure 4.3. Proportion of aggregates in each size class.

4.4.1.2 CLIMATE

Besides generic monthly summaries, climate data have been summarised into periods that relate to the crop and to the fertiliser (soil sampling) periods (Table 4.3). The crop growth period was from 21 October 2004 to 16 February 2005 and was drier than average (Figure 4.1). The fertiliser/soil monitoring period was from 7 October 2004 (Tiny tag soil temperature data only; Table 4.3) or 21 October 2004 (all other variables) to 16 September 2005. Rainfall, solar radiation (SR) and GDD data are the monthly totals of the data collected. Air and soil temperature data are the daily mean for the month. Maximum soil water deficit (SWD) for the potato crop was estimated using the Potato Calculator (Jamieson et al., 2006); a Templeton soil was used and the relevant management variables and climate data from the nearby weather station were used to run the model. The model was calibrated by adjusting appropriate phenological variables both in the cultivar file (e.g. maximum GAI, GDD to maximum GAI) and in the model interface so that the simulated stages of development (e.g. LAI estimates and time to complete senescence) fell as close as possible to those measured in the field. No irrigation was applied to the crop so maximum SWD was much greater than the SWD threshold of 40 mm after which yield is reduced, reported by Jamieson (1985).

Table 4.3. Key climate variables over the experimental period. SR is total solar radiation; GDD, growing degree days (above base temperature of 7°C) (Sands et al., 1979); SWD, maximum soil water deficit. WeatherPro soil temperature is the mean soil temperature measured 10 cm under pasture adjacent to the experiment; Tiny tag soil temperature is the mean (n = 3) of that measured at 7cm depth in the fertiliser incorporation zone prior to, and whilst the potato crop was growing. Note data for the month of October began on 21 October 2004 except for the Tiny tag data which began on 7 October 2004.

Month	Total rainfall (mm)	Total SR (MJ/m^2)	Mean air temp (°C)	Total GDD (°C)	Maximum SWD[a] (mm)	Mean Soil temperature	
						WeatherPro	Tiny tag
October	23	230	10.9	98.0	15	15.9	15.6
November	109	718	20.9	264.8	25	16.4	17.5
December	135	749	21.3	278.1	90	19.1	17.4
January	24	775	23.2	365.3	145	20.6	20.3
February	113	562	24.1	365.6	110	21.1	21.3
March	103	505	23.4	363.3	-	19.3	-
April	71	473	21.4	256.9	-	15.4	-
May	315	308	18.4	216.3	-	13.9	-
June	127	267	14.7	100.6	-	10.1	-
July	160	285	15.4	126.5	-	10.4	-
August	94	405	15.7	121.0	-	11.2	-
September	41	240	17.5	98.4	-	13.2	-
Total crop[b]	403	2903	17.2	1289	N/A	18.9	18.4
Total fertiliser[c]	1314	5539	14.8	N/A	N/A	15.6	-

[a]estimated using the potato calculator (Jamieson et al., 2006), see text for details.
[b]data from potato sowing to harvest date (21 October 2004 to 22 February 2005 respectively).
[c]data from potato sowing date to last soil sample date (16 September 2005).

4.4.2 CROP

4.4.2.1 GROWTH AND DEVELOPMENT

There were no significant differences among treatments in LAI estimates on either SD (Table 4.5). However, pre-planting measurements of soil mineralisable N showed a significant ($p = 0.005$) but weak ($R^2 = 0.15$) correlation with estimated LAI on 6 January 2005 (78 days after planting). This suggested that soil N availability (or a related factor) was having some influence on canopy development.

Results from the plant samples collected on 6 January 2005 indicated that yellow (N deficient) plants had about a 26 % lower N concentration (2.45 % w/w) compared with dark green (N sufficient) plants (3.33 % w/w) ($p = 0.05$; $df = 7$). Sufficient N concentration values for potato tops (whole shoots) at 73 and 88 days after planting are reported to be 3.00-4.89 % w/w respectively and low values (nearing deficiency symptoms) are 2.87-3.43 % w/w (Jones, 1966). Shoot P concentrations were not

significantly different (P >0.05) between the yellow and dark green plants (average 0.24 % w/w P). This value is slightly above the sufficient range of 0.18-0.22 % w/w reported for (post flowering) potato tops by Bingham (1966). Thus, these results suggest that N was more limiting than P.

The applications of Wuxall Amino in mid January 2005 did little to alleviate N deficiency symptoms which persisted over the remainder of the season which is not surprising given the small amount of N (10.5 kg N/ha) that was applied. Although not measured, the comparatively large amount of organic N applied in BioPhos (up to 70 kg N/ha; Table 4.1) also did not appear to reduce N deficiency symptoms in these treatments.

Figures 4.4 to 4.8 show the field experiment, how it was laid out in the field and the growth and development of the crop canopy throughout the season.

4.4.2.2 PLANT PHOSPHORUS CONCENTRATION

Shoot and tuber P concentrations are presented in Table 4.4. Shoot samples collected on 22 February 2005 were discarded (as mentioned in section 4.3.5), hence data is not presented.

Table 4.4. Phosphorus concentration (% w/w) of the shoots and tubers. Values with the same suffix letter are not significantly different.

		Shoot		Tuber
Treatment		2-Dec-04	17-Jan-05	22-Feb-05
	Control	0.33 a	0.16	0.18
Broadcast	BioPhos	0.36 b	0.17	0.19
	BioSuper	0.42 c	0.19	0.21
	RPR	0.36 b	0.18	0.19
	F-pr	<0.001	0.363	0.123
	$LSD_{0.05}$	0.03	N/A	N/A

Figure 4.4. The planted rows on the day of planting (20 October 2004).

Figure 4.5. The crop on 3 December 2004. The white flags indicate the two central harvest rows of the (main) plots. Subplots were arranged along the length of the main plots.

Figure 4.6. The potato crop on 15 December 2004 (early flowering). LAI at this stage was ca. 1.4 m^2/m^2.

Figure 4.7. The crop on 6 January 2005 (late flowering). Note this was the point in time when LAI was about at its maximum; 2.5 m^2/m^2.

Figure 4.8. The potato crop on 17 January 2005 (post flowering). Note the N deficiency symptoms (yellowing).

BioSuper had significantly higher shoot P concentration on 2 December 2004 than BioPhos and RPR, which had a higher P concentration than the Control. By 17 January 2005 (102 DAFA) there were no differences among treatments in shoot P concentration (mean 0.17 %). There were also no differences among treatments in tuber P concentration (mean 0.19 %) or uptake (mean 13.3 kg P/ha) at final harvest (22 February 2005).

4.4.2.3 YIELD AND BIOMASS

Measurements of soil mineralisable N and Bic-P at the start of the season and plant population density at final harvest were used as covariates when analysing the final harvest data. However, these were ineffective (i.e. not significant) so the unadjusted data are presented.

Total shoot biomass (mean 1.3 t DM/ha) and tuber biomass (7.5 t DM/ha) were unaffected by the fertiliser treatments (Table 4.5). Total tuber yield (35.2 t FW/ha) was also unaffected by fertiliser treatment (Table 4.6).

A positive relationship was found between soil MC measured on 16 February 2005 and total tuber yield ($P<0.001$; $R^2 = 0.56$; Figure 4.9) measured on 22 February 2005. This indicated that soil MC (or a related factor) at or leading up to final harvest had a moderate influence on crop growth and yield.

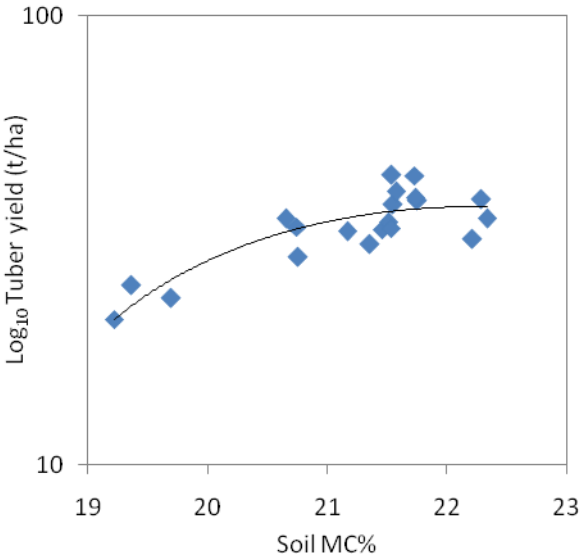


Figure 4.9. The relationship between soil moisture content (% w/w) measured on 16 February 2005 and log_{10} of tuber yield measured on 22 February 2005. $P<0.001$; $R^2 = 0.56$.

Infrequent rainfall and lack of irrigation lead to significant SWDs developing during the mid to later part of the season which reduced water availability and limited potential yield (Jamieson, 1985; Martin et al., 1992) (see section 4.5 and Appendix 1).

Multiple linear regression (Genstat V9) using soil mineralisable N (at the start of the season) and soil MC (16 February 2005) accounted for 55.3 % of the variation in total shoot biomass ($P<0.001$). Including plant population density in the regression model increased the variability accounted for to 62.7 %. Soil MC (16 February 2005) accounted for 55.9 % of the variation in total tuber yield ($P<0.001$) and multiple linear regression including soil MC (16 February 2005) and plant population density (final harvest) increased the variance accounted for to 74.2 % ($P<0.001$); but including mineralisable nitrogen did not improve the regression model.

There was no treatment effect on tuber yield in any size class at the 5 % probability level (Table 4.6). In size class D there were significant differences among treatments in tuber numbers/m^2 (P = 0.03), whereby broadcast-RPR < banded-BioPhos, banded-RPR2, banded-RPR3, Control and broadcast-BioSuper; broadcast-BioSuper > banded-BioSuper, broadcast-BioPhos and broadcast-RPR. However at the lower 10 % probability level there were differences among treatments in tuber yield in size class A and D. There were also significant differences among treatments in the number of tubers/m^2 at the 10 % probability level in size class A (Table 4.6), but these will not be discussed because of the low significance.

Soil MC measured on 3 December 2004 was slightly but significantly higher in the Control plots (23.7 %) than in the broadcast- BioSuper (22.2 %), BioPhos (21.6 %) and RPR (21.3 %) plots (P = 0.02; data not shown) but the reason for this is unclear.

Regression analysis on the broadcast-fertiliser and Control treatments (data not shown) indicated that yield or tuber number in size class A was not correlated with soil MC on 3 December 2004 or 16 February 2005 which suggests that soil moisture did not influence these (size class A) results. However, soil MC on these dates was weakly correlated with yield (P = 0.097; R^2 = 0.10) and tuber number (P = 0.089; R^2 = 0.11) in size class D indicating that soil MC or a related factor on these dates had a slight influence on the yield and number of large (7.5-10 cm) tubers.

The results from the common scab (*Streptomyces* spp.) scores are shown in Table 4.7. The percent area infected was significantly higher in banded-BioPhos than all other treatments except banded-RPR3. Banded-RPR3 was higher than broadcast-BioPhos and banded-BioSuper and banded-RPR1. There were no other significant differences among treatments in the percent area infected.

There were no treatment effects in the percentage of tubers infected or the severity (Table 4.7). Contrast analysis on the percent tubers infected indicated a 'slight' difference between broadcast- BioSuper and BioPhos (P = 0.074). Banded- BioPhos,

BioSuper and RPR2 and RPR3 were also significantly different from broadcast-BioSuper at the 10 % probability level.

Table 4.5. In season estimates of crop leaf area index (LAI) and measured shoot and tuber biomass at final harvest.

Treatment		LAI (16-Dec-04)	LAI (6-Jan-05)	Shoot biomass (t DM/ha)	Tuber biomass (t DM/ha)
	Control	1.4	2.7	1.3	7.8
Broadcast	BioPhos	1.4	2.4	1.1	7.1
	BioSuper	1.4	2.4	1.1	7.6
	PR	1.3	2.2	1.0	6.9
Banded	BioPhos	1.3	2.7	1.3	7.4
	BioSuper	1.4	2.4	1.1	7.8
	RPR1	1.4	2.5	1.7	7.6
	RPR2	1.4	2.6	1.5	7.7
	RPR3	1.4	2.7	1.6	8.0
	F-pr	0.971	0.191	0.350	0.466
	$LSD_{0.05}$	N/A	N/A	N/A	N/A

Table 4.6. Tuber yield and size distribution at final harvest.

		Size class A (0-2.5cm)		Size class B (2.5-5cm)		Size class C (5-7.5cm)		Size class D (7.5-10cm)		Total (all size classes)	
Treatment		No. Tubers (m^{2-})	Yield (t/ha)	No. Tubers (m^{2-})	Yield (t/ha)	No. Tubers (m^{2-})	Yield (t/ha)	No. Tubers (m^{2-})	Yield (t/ha)	No. Tubers (m^{2-})	Yield (t/ha)
	Control	2.6	0.2	15.0	5.7	15.5	23.9	1.9	6.8	35.0	36.7
Broadcast	BioP	1.8	0.1	14.9	6.3	16.0	24.7	0.6	2.3	33.4	33.5
	BioS	3.4	0.2	12.4	5.4	16.2	23.6	2.1	6.3	34.1	35.5
	RPR	2.4	0.2	14.7	5.4	16.4	25.2	0.2	0.5	33.7	31.3
Banded	BioP	1.6	0.1	14.5	5.8	17.0	25.5	1.3	4.3	34.4	35.7
	BioS	2.5	0.2	14.3	6.7	17.0	26.0	0.8	2.6	34.6	35.6
	RPR1	0.6	0.0	13.6	6.0	17.1	25.7	1.2	3.9	32.4	35.7
	RPR2	1.2	0.1	11.1	5.0	16.4	25.2	1.6	5.3	30.2	35.6
	RPR3	3.4	0.2	12.6	5.8	16.8	25.8	1.8	5.8	34.6	37.6
	F-pr	0.076	0.081	0.773	0.942	0.991	0.997	0.034	0.082	0.861	0.458
	$LSD_{0.05}$	1.6	0.1	N/A	N/A	N/A	N/A	1.0	3.5	N/A	N/A

Table 4.7. Tuber common scab (*Streptomyces* spp.) scores. Severity was calculated by multiplying the percentage of tubers infected by the percent area infected / 100.

Treatment		% area infected	% tubers infected	Severity
	Control	9.2	15.1	1.4
Broadcast	BioP	5.4	20.3	1.1
	BioS	8.0	9.7	0.8
	RPR	8.2	15.8	1.3
Banded	BioP	17.2	21.5	3.7
	BioS	4.8	19.6	0.9
	RPR1	3.6	15.6	0.6
	RPR2	10.0	20.3	2.0
	RPR3	13.2	21.3	2.8
	F-pr	0.048	0.502	0.2
	$LSD_{0.05}$	6.8	N/A	N/A

4.4.3 SOIL

4.4.3.1 PH

There were no significant differences in soil pH among the Control and the broadcast-RPR and BioPhos treatments on any SD (Table 4.8 and Figure 4.10). Broadcast BioSuper had a significantly lower soil pH than the Control, and broadcast-RPR and BioPhos treatments on the last three SDs (Table 4.8).

The drop in soil pH in BioSuper (Figure 4.10) was the result of S^o oxidation, which was likely also to be responsible for the increase in Bic-P in this treatment.

Table 4.8. Changes in soil pH over time. Mean pH at the start of the experiment was 5.65. DAFA = days after fertiliser application.

DAFA	14	57	132	344
Date	21-Oct-04	3-Dec-04	16-Feb-05	16-Sep-05
Control	5.58	5.93	5.85	5.83
RPR	5.59	5.93	6.00	5.84
BioP	5.53	5.86	5.93	5.92
BioS	5.56	5.36	5.55	5.45
F-pr	0.035	<0.001	0.016	<0.001
LSD	0.14	0.19	0.29	0.14

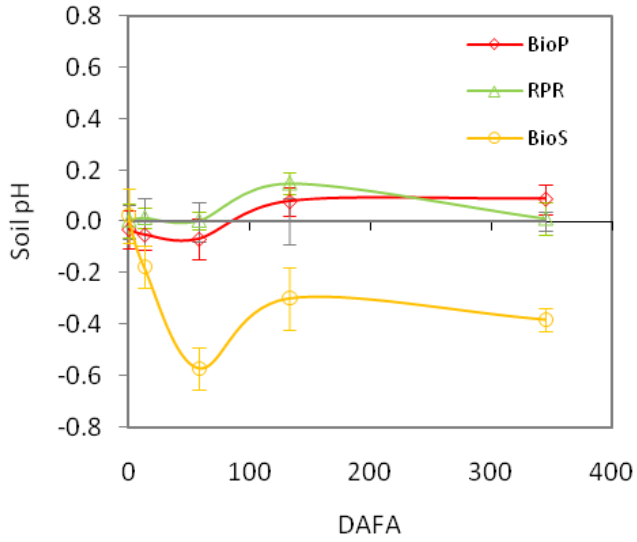


Figure 4.10. Changes in soil pH over time (days after fertiliser application; DAFA) for RPR, BioPhos (BioP) and BioSuper (BioS) applied at 678 mg P/kg soil relative to the Control (y-axis set to zero, with error bars centred on the x-axis). Error bars are $^{+}/_{-}$ SEM.

4.4.3.2 Bic-P

Changes in Bic-P for RPR, BioPhos and BioSuper were adjusted so that they were relative to the Control Bic-P, as was done in the laboratory experiment. However, there were some plots with consistently high values due to spatial variability so data was scaled to account for this variability. The scaling factor (SF) was calculated based on the proportional difference between fertiliser-treatment and Control data within replicates at the start of the experiment:

Equation 5

$$SF = \text{Bic-P}_{control}^{i} / \text{Bic-P}_{x}^{i}$$

Where $\text{Bic-P}_{control}^{i}$ is the Bic-P of the Control in the i^{th} replicate and Bic-P_{x}^{i} is the Bic-P of fertiliser-treatment x in the i^{th} replicate.

This adjustment was not required in the laboratory experiment because the soil was sieved so it was assumed to have a relatively homogenous Bic-P concentration. Each plot had its own individual SF.

The SF was used to adjust (by multiplying) data points on each SD so that Bic-P_x^i at the start of the experiment (7 October 2004) equalled Bic-$P_{control}^i$ but varied thereafter. The mean Bic-P for the Control (and each fertiliser-treatment) on this SD was 7.8 $^+/_-$ 0.9 µg/g. Data on subsequent SDs exhibited much less variability than that prior to scaling with mean CVs before and after scaling of 0.58 and 0.29 respectively.

Table 4.9 shows the adjusted Bic-P data.

Table 4.9. Changes in Bic-P (µg/g) relative to the Control at an application rate of 678 mg P/kg soil (equating to 488 kg P/ha). Note Control values were not included in the ANOVA. The mean Bic-P at the start of the experiment for the Control treatment was 7.8 µg/g; the unadjusted mean of all treatments at the start of the experiment was 9.5 µg/g (Table 4.2).

DAFA	14	57	132	344
Date	21-Oct-04	3-Dec-04	16-Feb-05	16-Sep-05
Control	2.4	14.0	8.2	7.8
RPR	1.7	-0.3	1.7	2.5
BioP	2.2	0.8	3.3	3.8
BioS	2.8	2.4	6.8	11.0
F-pr	0.274	0.161	0.009	<0.001
LSD	N/A	N/A	2.8	3.4

Bic-P fluctuated significantly over time. In the Control treatment, Bic-P was significantly lower at 14 DAFA than all other SDs, and was significantly higher at 57 DAFA than at all other SDs (Table 4.9).

Bic-P was significantly lower in the Control than all other treatments at 14 DAFA, however at 57 DAFA none of the treatments were significantly different. This may have been the result of P immobilisation by soil microbes and/or P uptake by the crop. At 132 and 344 DAFA, Bic-P in BioSuper and BioPhos was higher than the Control but RPR was not.

Increases in Bic-P over time were greatest in BioSuper, which had significantly higher Bic-P than RPR and BioPhos on the last two SDs (132 and 344 DAFA). Differences between RPR and BioPhos were not significant on any SD, as was generally the case in the laboratory experiment. However, BioPhos was significantly higher than the Control on the last two SDs.

Models of the changes in Bic-P over time (Equation 6) were generated based on the assumption that the models will follow similar trends to those generated in the laboratory study, albeit at a slower rate, and were to be used to calibrate the ΔBic-P models from the laboratory study.

Equation 6

$$\Delta Bic\text{-}P = -B(1-R^{x})$$

where Δ*Bic-P* is the Bic-P; *B* the asymptote parameter; *R* the curve fitting parameter and *x* the DAFA.

Given that there were no significant differences in Bic-P between RPR and BioPhos on any SD in the present (field) and laboratory studies, a common curve was fitted to these treatments. The parameter values of the fitted curves are shown in Table 4.10.

Table 4.10. Parameters for the exponential equation ($\Delta Bic\text{-}P = -B(1-R^{x})$) describing the changes in Bic-P (*ΔBic-P*; µg/g) over time (*x*; DAFA) at an application rate of 678 mg P/kg soil. Note that a single curve was fitted for RPR and BioP.

	R		B			
Treatment	Value	SE	Value	SE	R^2	F pr
RPR+BioP	0.993	0.005	-3.47	0.986	0.21	<0.001
BioS	0.995	0.003	-13.25	4.007	0.61	<0.001

The fit of these models to the data were highly significant (P<0.001; Figure 4.11) although it did not fit the data as well as the laboratory models did with much lower R^2 values (compare R^2 values in Table 3.8 and Table 4.10). This was attributable to the greater variability and the drift in the data in the present (field) study. The standard errors (Table 4.10) suggest that the *B* parameter for BioSuper was significantly higher than RPR and BioPhos (as the data presented in Table 4.9 suggests it should be, and as found in the laboratory study; Figure 3.7) but the *R* parameter was not significantly different.

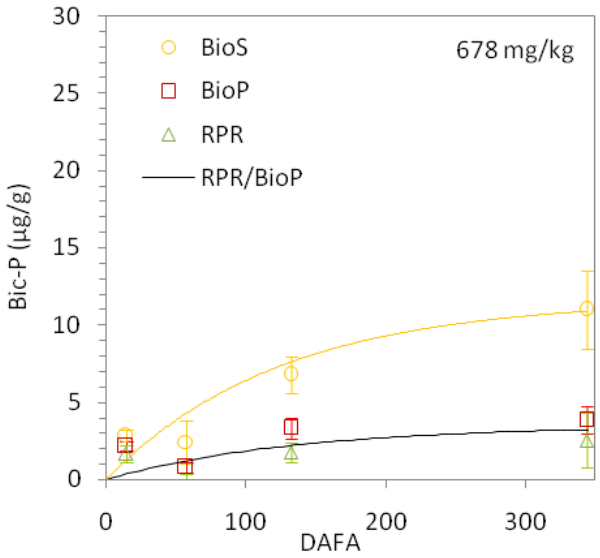


Figure 4.11. Changes in Bic-P over time (DAFA; days after fertiliser application) for RPR, BioPhos (BioP) and BioSuper (BioS) applied at 678 mg P/kg soil. Note that a single curve was fitted for RPR and BioP. Model parameters are set out in Table 4.10. Error bars are $^{+}/_{-}$ SEM.

4.5 Discussion

Mineralisable N, Bic-P and soil moisture displayed significant variability among plots which confounded the analysis and interpretation of the data. Data indicated that crop growth and development was more limited by water and N than P:

1. LAI estimates were correlated with soil mineralisable N level measured at the start of the season.

2. The majority of the crop was deficient in N, but not P, around the time of flowering.

3. Soil mineralisable N levels measured at the start of the season and soil MC at final harvest accounted for ca. 50 % of the variability in shoot biomass, as did soil MC for total tuber yield and tuber biomass. The amount of Bic-P present in the soil at the start of the season was variable but did not correlate significantly with any of the crop variables measured during the season.

Nitrogen deficiency symptoms increased in all plots throughout the life of the crop despite small foliar and soil applications of a Wuxall Amino to all plots and significant amounts of (organic) N present in BioPhos (up to 70 kg N/ha). Moreover, low soil moisture levels slow down N mineralisation rates and crops struggle to take up N from dry top soil, preferring to take it up (if present) from deeper, moister layers of the soil profile (Reid and Shaw, 2008). It is thought that regular irrigation would have helped alleviate the variability in soil moisture (water stress) and enhanced N uptake, P uptake and crop growth.

Jamieson (1985) showed when SWD > 40 mm the yield response for potatoes was 45-50 kg/ha for each mm of water applied and that the response to water was linear regardless of the severity of the SWD. Potatoes also respond well to N (Jenkins and Mahmood, 2003; Jamieson et al., 2006). The Potato Calculator (Jamieson et al., 2006) was used to estimate the yield loss resulting from N and water shortages.

The Potato Calculator modelling analysis, which used the weather data collected from the WeatherPro weather station (Table 4.3) and the relevant soil data (Table 4.2), and which assumes that P (and all other nutrients) is not limiting, indicated that crop growth and development were severely restricted (in Figure 4.12 compare "Tuber FW potential" with "Tuber FW").

A Templeton soil was used for the simulations because this was considered the closest approximation (in the soil profile database of the model) of the water holding capacity and texture of the soil (Hikuwai fine sandy loam) used in both the field and laboratory studies. Soil water deficit at the start of the season was set to nil. The cultivar used was Russet Burbank as this was the most reliable (personal communication; Robert Zykowski)[11]. Rooting depth was 0.7 m. Maximum GAI was set to 4.8 because this is a close approximation of the point of 100 % radiation interception (Stone et al., 1999); GAI above 4.8 is not beneficial and probably not achievable given that the crop was organic and therefore N limited. The model was calibrated by adjusting appropriate phenological variables both in the cultivar file (e.g. maximum GAI, GDD to maximum

[11] Crop modeller, Crop and Food Research, Lincoln.

GAI) and in the model interface (e.g. potential canopy gone date) so that the simulated stages of development (e.g. LAI estimates and time to complete senescence) were close to those measured in the field. Full canopy senescence date fell on 22 February 2005 (the date of harvest).

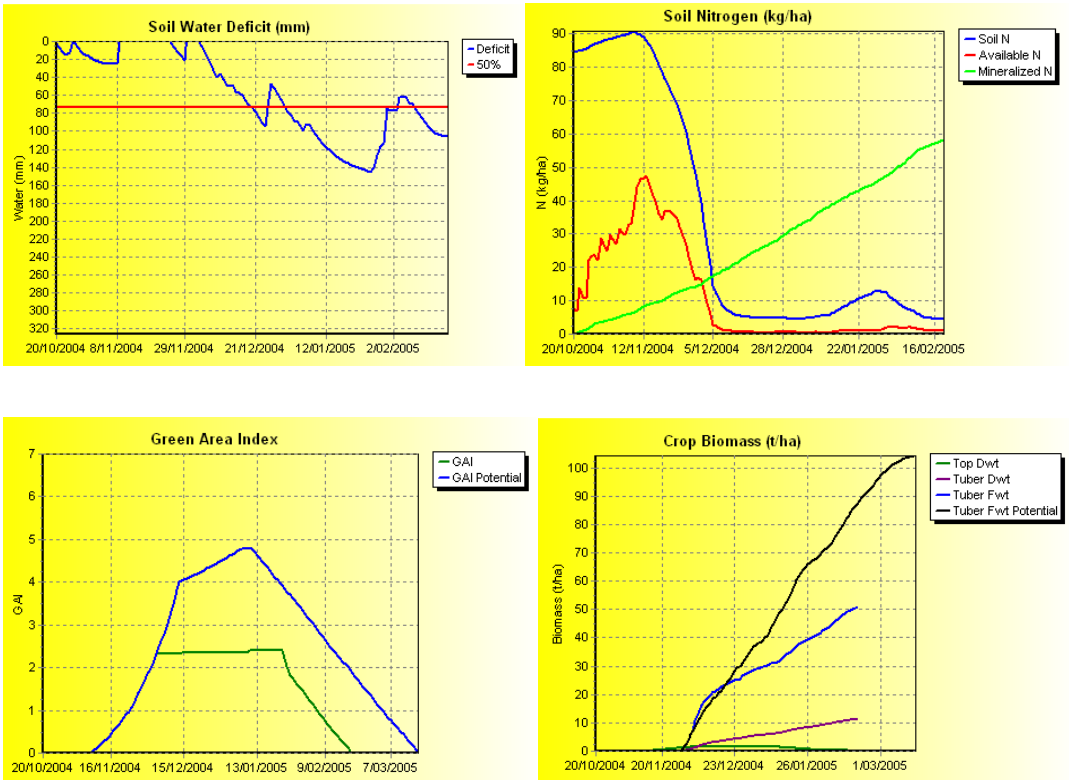


Figure 4.12. Simulated SWD, soil (mineral) nitrogen, green leaf area index (GAI) and crop yield/biomass graphs from the Potato Calculator (Jamieson et al., 2006) for the potato crop grown in the field experiment. The time frame (x-axis) spans the potential growing period of the crop which includes the actual growing period, from planting to harvest.

Canopy development (GAI) in the simulation (Figure 4.12) followed similar trends to the LAI measurements recorded in the field (Table 4.5) but was well below potential. Yield and biomass accumulation were well below potential (Figure 4.12). Total simulated tuber yield was 50.7 t/ha (cf. an achieved mean tuber yield of 35.2 t/ha). Soil water deficit was a major limitation in the later part of the season (Figure 4.12). Increasing the model's soil mineral N parameter and/or applying N at planting increased canopy development early in the season but had little effect on maintenance of GAI late in the season (data not shown). Factors contributing to the 15.5 t/ha yield gap (potential yield – achieved yield) are unknown but are most likely to be related to

insufficient calibration of the model, with a smaller part to weeds and pests and disease which are not accounted for in the model.

Thus, in the early part of the season the main limiting factor was nitrogen, whereas in the later part of the season the main limitation was water. Applying irrigation and N to meet crop demand increased the simulated yield to 104 t/ha (Appendix 2). For this the crop required 320 kg/ha of N and 250 mm of irrigation.

The P concentration of the shoots on 3 December 2004 (57 DAFA) was greatest in BioSuper and lowest in the Control, although even the Control plants contained 'sufficient' P concentrations at this point in time according to (Bingham, 1966). These differences in plant P concentration among the fertiliser treatments coincided with the only point in time while the potato crop was growing where there were no differences among treatments (including the Control) in soil Bic-P concentrations (i.e. 57 DAFA). By 17 January 2005 (when there were no significant differences in the P concentration of the shoot material) P concentration of the shoots was getting marginal (Bingham, 1966), although this may have been attributable to the stress caused by low water (Fisher, 1980) and possibly N availability. Tuber P content and uptake were unaffected by the treatments and within the range deemed to be sufficient for potato tubers (Bingham, 1966).

Clearly, if a higher yield was achieved a greater amount of P would have been required by the crop. Thus it is possible that a fertiliser response may have occurred if conditions during the last half of the season were better, because differences in plant P concentration had emerged early in the season. Irrigation would have helped with this, as would have higher N availability. The best way to increase N availability in organic cropping systems is to grow leguminous green manure crops, or use land that has been in pasture for a reasonable period of time (Watson et al., 2002). As mentioned in section 1.1 most ECOPT growers do not follow these kinds of cultural practices. So, any plans that ECOPT growers have to increase the P availability of the soil, or positive expectations resulting from this, must be weighed up against the benefits that addressing other production limiting factors (e.g. weeds, pest and disease, irrigation

and N nutrition) may also impart. In other words, all of these potential limiting factors must be addressed for optimal yields to be achieved.

Soil pH was generally lower in the BioSuper plots than RPR and BioP, however this was only apparent from 57 DAFA onwards. This indicates a lag period (>14 but <57 DAFA) before S^o oxidation creates a drop in pH. Rajan and Edge (1980) found this lag period to be about two weeks. Because dissolution of PR is a consumer of protons a proportion of the protons generated during S^o oxidation are neutralised during PR dissolution (Lee et al., 1987). Potatoes are relatively tolerant of low soil pH and yield well at pH levels much lower than was witnessed in the broadcast BioSuper treatment (Table 4.8) (Burton, 1989), therefore the drop in soil pH as a result of S^o oxidation in BioSuper would not have affected its yield potential. The liming effect of RPR and BioPhos was negligible, as was often the case in the study by Lewis et al. (1997).

Common scab is particularly virulent in dry conditions and attacks only the young, actively growing tubers (Burton, 1989). Furthermore, infection risk decreases as pH decreases and infection is infrequent at pH <5.2 (Burton, 1989). Results indicate that the differences in soil pH fluxes over time did not affect the common scab scores (Table 4.7). The increase in percent area of the tubers covered by common scab in banded BioPhos is unknown because the soil pH fluxes in BioPhos were similar to RPR (Table 4.8) which was not as affected by the disease. Applying irrigation may have reduced the severity of common scab in this study.

Considerable fluctuations in Bic-P were apparent in this study. Tate et al. (1991) showed that Bic-P can fluctuate markedly (from 5 to 20 µg/l) over periods less than a month due to seasonal fluxes in organic matter mineralisation, plant uptake and immobilisation from soil microbes. The fluctuations in Bic-P over time presented here (Table 4.9) were probably caused by similar processes, and may have been exacerbated by cultivation. Cultivation increases microbial activity, which may immobilise labile P_i as apparent over the 0-14 DAFA period in the present study; followed by mineralisation (increase in labile P_i) during spring and early summer, as was often found in the study by Tate et al. (1991).

By the end of the crop growth period (132 DAFA) BioSuper had increased Bic-P by ca. 80 %; from 8.2 to 14.9 µg/g (Table 4.9). The RPR and BioPhos treatments only increased Bic-P by ca. 20 % to ca. 10.0 µg/g. Linear regression with groups (fertiliser type) showed that there was a significant negative correlation between Bic-P and soil MC (both) measured on 16 February 2005 ($P = 0.002$; $R^2 = 0.77$) (Figure 4.13). BioSuper and RPR had significant negative slopes (-1.8 and -1.3 µg/g/MC % respectively) whereas the slope of BioPhos was not significantly different from zero. A significant but weaker correlation between Bic-P and soil MC measured on 9 December 2004 was apparent (not shown), but multiple linear regression using both soil MC sampling dates did not account for any more variation than the original (Figure 4.13) regression. Kanabo and Gilkes (1988b) also showed a positive correlation between soil moisture and changes in Bic-P.

One possible reason for the unexpected relationships in Figure 4.13 is P uptake by the potato crop. Evidence of a positive relationship between tuber yield and soil moisture measured on 16 February 2005 was presented above, and although there were no differences in P uptake among treatments on this date it is possible that the plots with higher soil MC had more P taken up from them than the lower soil MC plots; because they yielded more. But why did this not occur in BioPhos? One possibility is that BioPhos may be better able to replenish Bic-P than RPR or BioSuper as the relationships shown in Figure 3.6 might suggest. The problem with this theory though is that it contradicts the ΔBic-P data and models presented in this and the previous chapter (3). Unfortunately there are no other leads to follow to explain this phenomenon, although irrigation may have alleviated the confounding influence that soil MC appears to have had.

Although it is not possible to directly compare the ΔBic-P models from the field and laboratory studies (because the application rates differed), the changes in Bic-P that occurred in the field study were generally much lower than what occurred in the laboratory study. At 155 DAFA in the field study, modelled Bic-P in RPR/BioPhos and BioSuper applied at 678 mg P/kg soil was 2.3 and 7.2 µg/g respectively. At 155 DAFA in

the laboratory study, actual (measured) Bic-P for RPR, BioPhos and BioSuper applied at 267 mg P/kg soil, were 8.2, 7.1 and 8.8 µg/g respectively, and for RPR at 533 mg P/kg soil Bic-P at 155 DAFA was 11.4 µg/g.

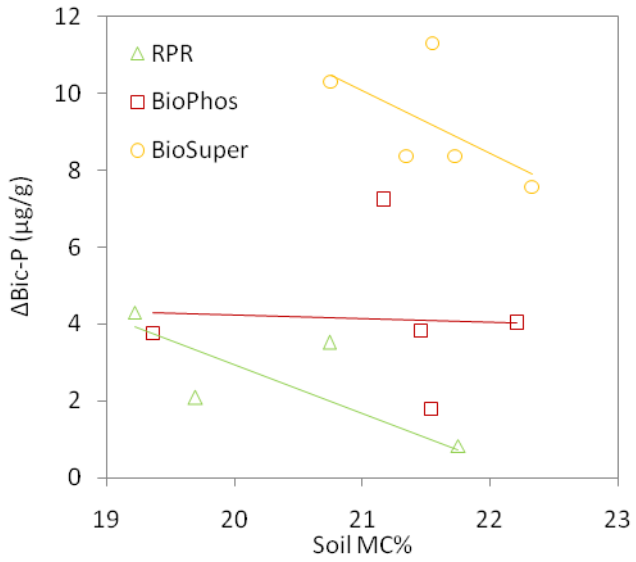


Figure 4.13. The relationship between changes in Bic-P and soil moisture content (Soil MC %) as measured on 16 February 2005. Note the missing data point for RPR (*y* = -0.1 when *x* = 21.7) was included in the grouped (by fertiliser type) regression (P = 0.002; R^2 = 0.77).

Despite this significant increase in Bic-P, BioSuper did not increase crop growth or yield of the potato crop, probably because water and N were the main limiting resources. To examine the effects that changes in Bic-P might have had if soil conditions were homogenous and there was no sampling error PARJIB (Reid, 2002) was used. A range of P response curves were generated for various scenarios including what occurred in this study; that when Bic-P was 8.5 µg/g, yield was 35 t/ha (Appendix 1). This particular P response curve indicated that when Bic-P at planting was increased by 2.8 µg/g (from 8.7 µg/g to 11.5 µg/g) as was the change in Bic-P for BioSuper at 14 DAFA (Table 4.9) the simulated yield response was 0.9 t/ha. However, if potential yield was set to 115 t/ha (which resulted in a simulated potential yield close to the potential yield forecast using the potato calculator when water and N weren't limiting; see Appendix 2) the forecast yield increase was 11.8 t/ha (Appendix 1).

In summary, the Potato Calculator and PARJIB modelling exercises showed that water and N were limiting crop growth and development, and that much greater P responses would probably have occurred if water and N were applied to meet crop demands. It could also be expected that delaying planting for a longer period after fertiliser application would further increase the yield response to applied P because of the ongoing increases in Bic-P after PR fertilisers are applied. Growing a green manure legume crop at the time of fertiliser application (e.g. in autumn) may result in even greater increases in plant-available P concentrations because of the positive effects that leguminous crops have on PR dissolution (Gerke et al., 1995; Hinsinger and Gilkes, 1995) (Chapter 2).

4.6 Conclusions

Ben Guerir RPR, BioPhos and BioSuper were applied in spring 2004 at a range of application rates; using banded and broadcast methods. Potatoes were grown and changes in soil pH and Bic-P measured. The crop was harvested in autumn 2005. The final soil samples were collected in spring 2005, ca. one year after initial fertiliser application.

Potatoes did not respond to any of the treatments despite moderate increases in Bic-P (particularly in broadcast BioSuper; 488 kg P/ha) and enhanced P uptake early in the growth of the crop (43 days after planting) in the broadcast treatments. Data suggests that water and N were more limiting than P. Indicators of this were i) SWD estimated using the Potato Calculator (Jamieson et al., 2006) indicated that the crop was under severe water stress over much of the last half of the crop growth (tuber bulking) period ii) LAI estimates were (loosely) correlated with soil mineralisable N levels measured at the start of the season iii) shoot samples taken around the time of flowering indicated that N was deficient in most of the crop iv) soil mineralisable N and soil MC accounted for a moderate amount of the variability (ca. 50 %) in shoot and tuber biomass and tuber yield and v) soil moisture at final harvest was significantly higher in the Control which also yielded more than the other treatments. Note that differences among plots in plant population density also influenced the results.

There were no significant differences between the broadcast and Control treatments in the percentage of the tuber surface area infected by common scab (*Streptomyces* spp.). However, there were differences among the banded treatments, and between the banded, broadcast and Control treatments, but the there were no clear patterns. For example, banded BioPhos had significantly more surface area infected by scab than broadcast BioPhos, even though they were applied at the same SPF concentrations. There were also no significant differences among treatments in the percentage of tubers infected with common scab or the severity of infection.

The increases in Bic-P and pH fluxes were much less than those that occurred in the laboratory study, as expected. Nevertheless, significant differences between treatments in changes in Bic-P over time were apparent. By the end of the crop growth period (132 DAFA) broadcast BioSuper, BioPhos and RPR, applied at 488 kg P/ha (678 mg P/kg soil), increased Bic-P by 6.8, 3.3 and 1.7 µg/l soil respectively. By 344 DAFA these changes were 11.0, 3.8 and 2.5 µg/g respectively. Apart from an anomaly on 57 DAFA (where Bic-P decreased in all treatments; possibly a combination of P uptake and immobilisation by soil micro-organisms over the preceding weeks), Bic-P increased over time. This increase was described using the equation $\Delta Bic\text{-}P = -B(1-R^x)$; where x is the number of days after fertiliser application. The changes in Bic-P over time for RPR and BioPhos were similar so a single model was used to describe them both. The B parameter for RPR and BioPhos was -3.47 ($^+/_-$ 0.986) for and BioSuper -13.25 ($^+/_-$ 4.007). Respective R parameters were 0.993 ($^+/_-$ 0.005) and 0.995 ($^+/_-$ 0.003).

By the end of the crop growth period, broadcast BioSuper (488 kg P/ha) decreased soil pH by 0.30 units, whereas BioPhos and RPR at the same application rate increased soil pH by 0.08 and 0.15 units respectively. By 344 DAFA these changes were -0.38, 0.09 and 0.01 respectively.

CHAPTER 5

5 INTEGRATING LABORATORY AND FIELD STUDIES

5.1 INTRODUCTION

The laboratory experiment was undertaken to provide information on the best rates to use in the field experiment and to generate models of PR dissolution, and changes in soil pH and Bic-P over time. The field experiment was conducted to calibrate the models of changes in Bic-P generated from the laboratory data, and to determine whether potatoes would respond to the same fertilisers as used in the laboratory study.

The changes in Bic-P were slower and of lower magnitude in the field study than in the laboratory study. Potatoes did not respond to any of the PR application treatments in the field study, which was limited by water and N availability. However, a modelling exercise using PARJIB (Reid, 2002) indicated that a significant crop response might have occurred under conditions where water and N were not limiting.

This chapter aims to explain the differences in the rates of change in Bic-P between the laboratory and field studies. In addition the laboratory and field data are integrated to calibrate the laboratory models for field conditions. These calibrated models are then used to provide information on the expected changes in Bic-P for RPR, BioPhos and BioSuper applied at various application rates and time intervals before planting (potatoes). This data was used in PARJIB to estimate the optimum economic application rates for each fertiliser based on a theoretical "time to reapplication" model. A theoretical model was used because there is little data published on the expected time frames between application and reapplication of PR fertilisers to maintain adequate soil plant-available P concentrations in cropping situations.

As was mentioned in the field study chapter (Chapter 4), the intended soil sampling strategy was not practicable because of problems that were had incorporating the

fertiliser with the soil (see section 4.3.3). Unfortunately this has affected the integrity of some of the following analyses because there is no firm evidence that the positive relationship between PR application rate and ΔBic-P found in the laboratory study occurred under field conditions. Nevertheless, this is an assumption that has been made because this relationship has been well documented (Hughes and Gilkes, 1986; Kanabo and Gilkes, 1988c; Rajan et al., 1991a).

5.2 CALIBRATING THE LABORATORY MODELS

5.2.1 APPROACH

Because the changes in Bic-P in the field study were slower than they were in the laboratory study the laboratory curves needed to be calibrated for field conditions. Also, because there were relative inconsistencies between the laboratory ΔBic-P models as application rate increased (mainly the result of unstable *R* values), these original laboratory models were smoothed.

Since there were no consistent relationships between the *R* parameter and application rate (see section 3.5) an average *R* parameter was used for all fertilisers. The relationships between application rate and *B* parameter presented in Figure 3.7 were used to smooth the models even further. Combined with the average *R* parameter these relationships were also used to generate ΔBic-P models for BioSuper at application rates of 67, 133 and 533 mg P/kg soil (since only 267 and 1333 mg P/kg soil were used for BioSuper in the laboratory study) and for all fertilisers applied at 678 mg P/kg soil (to correspond with the rate used in the field study).

To adjust for the slower rate of PR dissolution and ΔBic-P in the laboratory study, a result also found by Robinson and Syers (1991), and thought to be due to differences in pH and soil surface area (see section 5.4), the laboratory data were stretched along the *x*-axis (DAFA) so that the laboratory ΔBic-P *x*-axis value 155 DAFA fell on field *x*-axis value 344 DAFA and all other laboratory data points shift along the *x*-axis accordingly. From here the relationship (deviation) between the laboratory and field curves at 678 mg P/kg soil was calculated and the laboratory curves calibrated for field conditions.

5.2.2 OUTCOMES

5.2.3 CURVE SMOOTHING

The new smoothed curves (Figure 5.1) showed consistent shape and trends relative to application rate and over time for each fertiliser type. In contrast the original curves were inconsistent with some crossing over each other (e.g. Figure 3.4).

Parameter *B* values for the smoothed models are presented in Table 5.1. The (common) *R* value used was 0.975 (the lower and upper 95 % CI's for this were 0.972 and 0.977; R^2 = 0.96; F-pr <0.001), calculated from the original laboratory data.

Table 5.1. *B* parameter values for the smoothed curves (Figure 5.1). See Table 3.1 for treatment details/application rates.

Treatment	Parameter *B*
RPR*/BioP1	-0.75
RPR/BioP2	-4.16
RPR/BioP3	-7.62
RPR/BioP4	-11.06
RPR*/BioP5	-15.62
BioS1	-3.62
BioS2	-4.94
BioS3*	-7.62
BioS4	-12.94
BioS5	-28.94

* Parameter *B* fell outside the 95% CI of the estimate from the original model

The *B* parameter estimates of the new models were within the 95 % CI's of the original models for most treatments (data not shown). The exceptions to this were RPR1, RPR5 and BioSuper3 (Table 5.1). Most of the *R* parameter estimates of the new models were also within the 95 % CI's of the original models, except for RPR5, BioS3, BioS5 and BioP3. Although the new models did not fit the data quite as well as the original models, when all treatments were considered the models described the data well (R^2 = 0.92), although RPR1 and RPR5 were consistently underestimated (Figure 5.2). If RPR1 was excluded from the analysis the R^2 increased to 0.96 (*y = 1.02x-0.11*).

Thus, because the ability of the models to predict changes in Bic-P at the lowest application rate was clearly unsatisfactory, RPR/BioP1 and BioS1 were left out of any

further analysis. Therefore the minimum application rate used during all analyses and nutrient modelling scenarios henceforth is 133 mg P/kg soil.

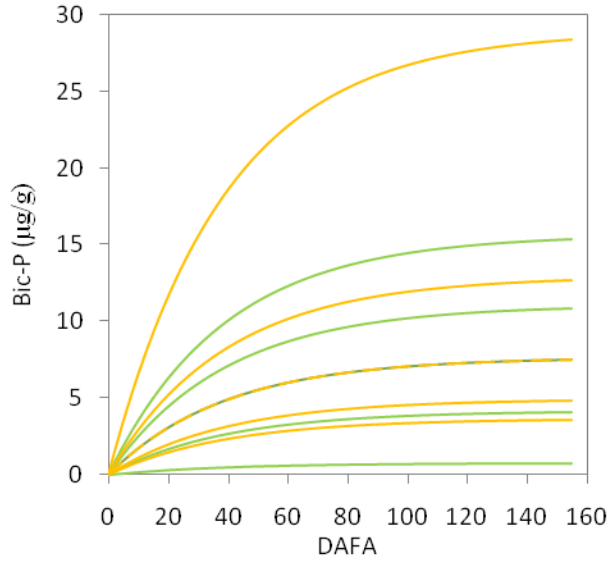


Figure 5.1. Smoothed curves of changes in Bic-P over time (days after fertiliser application; DAFA) for RPR/BioPhos (thin/green curves) and BioSuper (thick/gold curves) applied at 67, 133, 267, 533 and 1333 mg P/kg soil (stacked bottom to top respectively). Note BioS3 and RPR/BioP3 share the same curve.

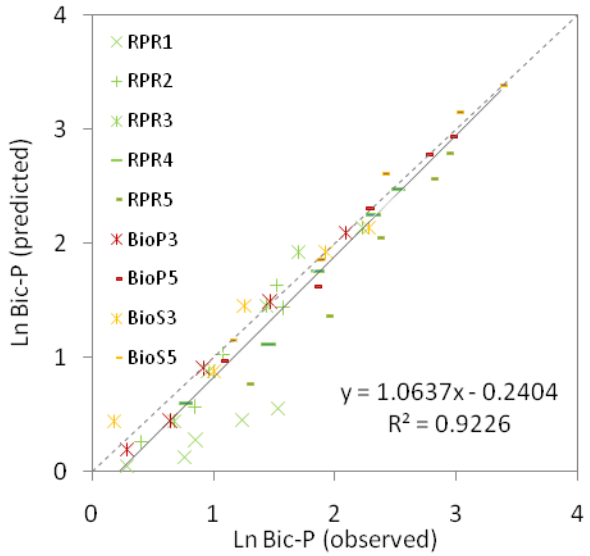


Figure 5.2. Natural log (Ln) of the predicted vs. observed Bic-P at 155 days after fertiliser application using the smoothed models (Table 5.1 and Figure 5.1). Note the dashed line is the 1:1 line; the equation and R^2 value shown relate to the regression (solid) line.

5.2.4 CURVE CALIBRATION

A hypothetical curve for 678 mg P/kg soil applied in the laboratory was generated using the relationship between the *B* parameter and application rate, and the common *R* parameter (Figure 5.3). As with the original laboratory curves this hypothetical curve was stretched along the x-axis as described above (data not shown).

The absolute difference among the curves on each DAFA was calculated (Equation 7) and the relationship plotted over time for each fertiliser (Figure 5.4). The 678 mg P/kg soil laboratory study curve was therefore made to lie on top of (i.e. calibrated for) the field study curve using this relationship (data not shown).

Equation 7.

$$A_{bs}D_{iff} = \Delta\text{Bic-}P_{lab}^{\ i} - \Delta\text{Bic-}P_{field}^{\ i}$$

Where $A_{bs}D_{iff}$ = the absolute difference in ΔBic-P values between the laboratory and field curves; $\Delta\text{Bic-}P_{lab}^{\ i}$ = the laboratory ΔBic-P value on the i^{th} DAFA; and $\Delta\text{Bic-}P_{field}^{\ i}$ = the field ΔBic-P value on the i^{th} DAFA.

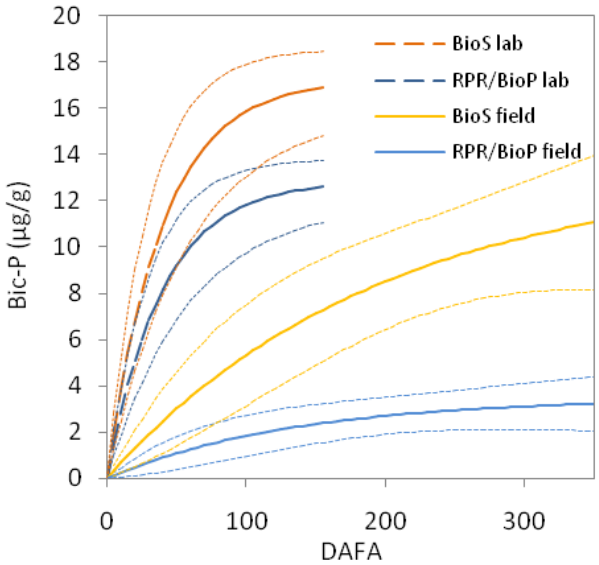


Figure 5.3. Changes in Bic-P over time (days after fertiliser application; DAFA) in the laboratory and field experiments for RPR/BioPhos and BioSuper applied at 678 mg P/kg soil. Dashed lines are the upper and lower 95 % CI's of the curves.

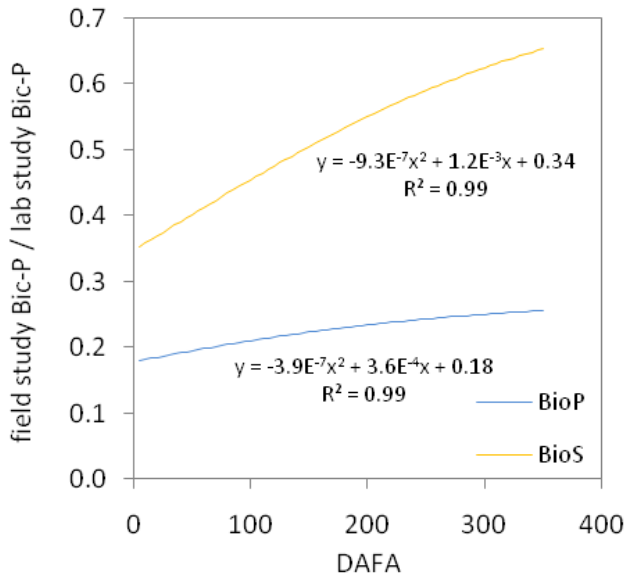


Figure 5.4. Modelled changes in the fraction of the Bic-P value from the field study compared with the DAFA (days after fertiliser application) adjusted laboratory study data (i.e. field study Bic-P / laboratory study Bic-P). Note this data was used to calibrate the suite of smoothed laboratory curves (Table 5.1 and Figure 5.3) for field conditions.

Figure 5.4 shows that the relative (fractional) difference between the laboratory and field ΔBic-P data decreases with increasing DAFA, almost, but not quite linearly. Moreover, RPR/BioPhos field data changed from 18 to 26 % that of the laboratory data over a 1 to 344 day period respectively, whereas BioSuper field data changed from 35 to 65 % that of the laboratory data over the same time period. When the unadjusted data are considered the respective differences were 8 to 19 % and 16 to 43 % for a 1 to 155 DAFA period. Figure 5.3 however, indicated that the absolute difference (Equation 7) increases initially then decreases as DAFA increases.

Parameters of the calibrated smoothed curves for changes in Bic-P over time for RPR/BioPhos and BioSuper are shown in Table 5.2.

Table 5.2. *B* parameter values for the smoothed calibrated curves. Parameter *R* was 0.994.

Fertiliser	Application rate (mg P/kg soil)	*B*
RPR/BioPhos	133	-1.134
	267	-2.078
	533	-3.015
	1333	-4.257
BioSuper	133	-3.721
	267	-5.737
	533	-9.741
	1333	-21.782

5.3 ECONOMIC ANALYSIS

ECOPT growers need to know how long after fertiliser application a yield response will occur and/or the maximum likely yield response to help make agronomic and economic decisions. This section uses PARJIB (Reid, 2002) generated P response curves and the calibrated smoothed curves of change in Bic-P over time (Table 5.2) to determine the optimum economic application rate for each fertiliser.

5.3.1 APPROACH

The smoothed calibrated models were used to simulate yield responses to the fertilisers applied at various rates and various lengths of time prior to planting potatoes using PARJIB (Reid, 2002). The soil data presented in Table 4.2 was used to run the model. Potential yield was set at 68 t/ha, as determined by the Potato Calculator (Jamieson et al., 2006) assuming rainfall was average and SWD at the start of the season was nil (see Appendix 3 for more details of the Potato Calculator simulation). The resulting P response curve is shown in Appendix 1 (P_{yld} = 68 t/ha).

The corresponding field application rates for 133, 267, 533 and 1333 mg P/kg soil were 96, 192, 384 and 959 kg P/ha, based on a soil incorporation depth of 9 cm and a soil

bulk density of 0.80 g/ml (section 4.3.2). For the sake of clarity these are referred to henceforth as 100, 200, 400 and 1000 kg P/ha respectively.[12]

An Olsen P of 8.5 µg/g was set as the starting point for changes in Olsen P (ΔBic-P), which equated to a simulated yield of 55.4 t/ha (see Appendix 1 and 3). Increases in Bic-P (from the smoothed calibrated curves) and yield (simulated in PARJIB; Figure 5.5) were cumulative from these starting points. Data points were included only for each additional unit increase in Bic-P using a threshold approach (i.e. 0.5 was rounded up to 1.0; 1.5 was rounded up to 2.0 etc). In other words, when Bic-P was greater than a given reported unit (e.g. 1 or 2 µg/g) then a yield response value was reported. So, the last data point was the last unit increase in Bic-P.

It should be noted that PARJIB was not designed to handle increasing Olsen P concentrations over the season as occurs when PR is applied, because PARJIB was built and calibrated using water-soluble P_i fertilisers (Jeff Reid, personal communication)[13]. So, one of the assumptions made during this analysis is that Bic-P does not increase after planting.

Optimum economic response rate was based on a fixed potato tuber price (see below) and fertilisers were applied six months before planting.

5.3.2 OUTCOMES

The simulations described above (Figure 5.5) indicate that BioSuper would be far superior to RPR or BioPhos at inducing a yield response. This was expected given the shape of the P response curve and the relationships between fertiliser application rate and the relative changes in Bic-P of each fertiliser.

[12] Note the sums and products of the various calculations in this section may not be exact due this to rounding.
[13] The developer of the PARJIB model.

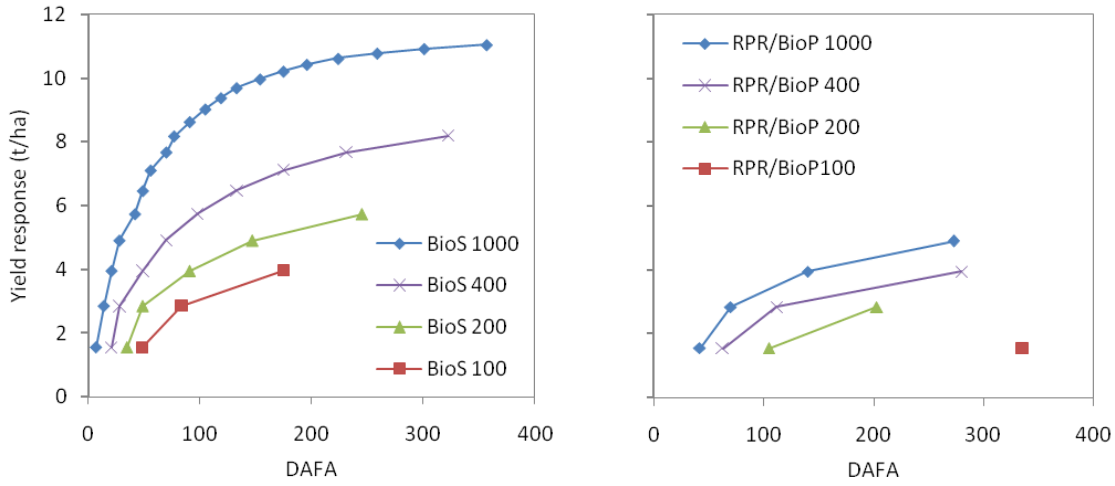


Figure 5.5. Forecast yield response in relation to application rate and days after fertiliser application (DAFA) for BioSuper (left) and RPR or BioPhos (right). Note the yield response is cumulative on top of 55.4 t/ha which is the potential yield simulated in PARJIB (Reid, 2002) when Bic-P is 8.5 µg/g (see Appendix 1 and 3). Suffix numbers 100, 200, 400 and 1000 relate to the application rate in kg P/ha (broadcast incorporated). Data generated by integrating the smoothed calibrated Bic-P curves (Table 5.2) and the PARJIB P response curve (Appendix 1).

For BioSuper applied at 1,000 kg P/ha the last simulated data point (or unit increase in Bic-P) was 357 DAFA; at 400 kg P/ha it was 322 DAFA; at 200 kg P/ha it was 245 DAFA and at 100 kg P/ha, 175 DAFA. For RPR and BioPhos applied at 1,000 kg P/ha the last simulated data point was 273 DAFA; at 400 kg P/ha it was 280 DAFA; at 200 kg P/ha it was 203 DAFA and at 100 kg P/ha, 336 DAFA. Note, RPR/BioPhos applied at 100 kg P/ha had only one data point because Bic-P increased by <1.5 units over the 365 DAFA simulation period.

Using this yield response data the cumulative return ($/ha) over the investment, over a six year period was calculated. The total cost of each fertiliser and application rate is shown in Table 5.3. Potato crops remove ca. 2 kg P/t of tuber dry matter (Wild and Jones, 1988), thus a 60 t/ha crop at 20 % dry matter would take up about 25 kg P/ha. Soil sorption and occlusion processes can tie-up large amounts of P released from and contained within PR's, the effects of which increase with time (Khasawneh and Doll, 1978). To account for these sorption and occlusion processes the length of time (n-years) between fertiliser applications required to maintain plant-available P concentrations and production was estimated using:

Equation 8.

$$\text{n-years} = (P_{rate} / 25 + 5) \times Log_{(3)}P_{rate}$$

Where P rate is the nominal P application rate (kg P/ha) assuming 25 kg P/ha are taken up by the crop each year. The $Log_{(3)}P_{rate}$ is an estimate of the decrease in the relative amount of plant-available P each year, which simulates the effects of sorption and other P loss processes. The '5' constant off-sets the $Log_{(3)}$ function at the lower application rates.

Unfortunately there was no functional data found in the literature on the time periods between capital applications and the drop in production for PR fertilisers in cropping systems. Consequently Equation 8 was estimated from information sourced from other studies (Khasawneh and Doll, 1978; Watkinson, 1994a; Garden et al., 1997). The justification for using an un-validated model such as this was that some attempt at estimating the PR persistence was required, and given the lack of relevant empirical data available there were no other viable options.

Other constraints and assumptions for these economic projections were the price for potatoes, $1,000 /t (at the farm gate)[14] ii) annual cultivation re-activated PR dissolution enough to adequately maintain Bic-P and production levels from year to year (off-setting P uptake by crops and soil sorption processes etc), iii) fertilisers were applied 6 months ahead of the first potato crop with potatoes grown every year.

Equation 8 states that at an application rate of 100 kg P/ha, another application of fertiliser would be required at the same rate after the second crop (i.e. by the end of year 2) to maintain production; at 200 kg P/ha an equivalent rate would be required after the third crop, at 400 kg P/ha after the fourth crop and at 1,000 kg P/ha after the seventh crop (Table 5.4).

[14] These are organic potatoes which receive a premium.

Table 5.3. The cost ($/ha) of each (nominal) application rate for each fertiliser used in the yield simulations and economic analysis. Data were based on August 2008 prices from Ravensdown (RPR and BioSuper [S^o]) and Ballance (BioPhos). P concentration of the fertilisers was based on data from Table 3.3. Includes transport (Gisborne to Ruatoria $50 /t)[15] and spreading ($30 /ha)[16].

	Nominal application rate (kg P/ha)			
Fertiliser	100	200	400	1000
RPR	480	940	1,850	4,580
BioPhos	400	760	1,490	3,690
BioSuper	560	1,140	2,270	5,690

Table 5.4. Phosphate rock persistence, fraction of P applied that was taken up by the crop and total P uptake between reapplications (assuming 25 kg P/ha/year). Note that the number of years between applications is based on Equation 8.

	Application rate (kg P/ha)			
Variable	100	200	400	1,000
P rate/25	4	8	16	40
Years between applications	2	3	4	7
Fraction of applied P taken up by the crop	0.50	0.38	0.25	0.18
Total P uptake between applications	50	75	100	175

All fertilisers applied at ≤400 kg P/ha had a positive net return by year 2, i.e. for the second crop (Table 5.5). Note that the economic differences between RPR and BioPhos (Table 5.5) are the result of differences in the costs of the fertilisers because changes in Bic-P and simulated crop response were the same for these two fertilisers. BioSuper applied at 100 kg P/ha returned about $3,312/ha (return on investment; ROI = 518 %) in the year of application (Table 5.5 and Table 5.6) whereas BioPhos and RPR applied provided much more modest returns than BioSuper across the range of application rates and time periods.

[15] The average price quoted by two local transport firms in September 2008.
[16] An estimated cost of bulk spreading.

Table 5.5. Cumulative net return on investment ($/ha) for RPR, BioPhos and BioSuper applied at 100, 200, 400 and 1,000 kg P/ha assuming that production would drop and fertilisers would need to be reapplied in year 3 for 100 kg P/ha, in year 4 for 200 kg P/ha, in year 5 for 400 kg P/ha and year 7 for 1,000 kg P/ha.

		Application rate			
Fertiliser	Year	100	200	400	1,000
RPR	1	-484	1,908	1,000	-627
	2	2,623	4,757	6,055	5,228
	3		7,606	10,006	10,131
	4			13,958	15,034
	5				19,937
	6				24,840
	7				29,743
BioPhos	1	-393	2,090	1,363	281
	2	2,714	4,939	6,418	6,136
	3		7,788	10,369	11,039
	4			14,321	15,942
	5				20,845
	6				25,748
	7				30,651
BioSuper	1	3,312	3,649	4,629	4,068
	2	7,263	10,211	13,880	15,941
	3		15,943	22,057	26,982
	4			30,234	38,023
	5				49,065
	6				60,106
	7				71,147

The apparent optimum economic application rate for maximum ROI over a 7 year cycle was 200 kg P/ha (applied every third year) for RPR and BioPhos, and 100 kg P/ha (applied every second year) for BioSuper (Table 5.6).

Table 5.6. Percentage return on investment (ROI) over 7 years for RPR, BioPhos and BioSuper applied at 100, 200, 400 and 1,000 kg P/ha assuming additional fertilisers were applied for the 100 kg P/ha application rate on years 3 and 5 with the ROI for year 7 being the average ROI over years 1 and 2; for 200 kg P/ha an additional 200 kg P/ha was applied in year 4 with the ROI for year 7 being the average ROI of years 1 to 3; for 400 kg P/ha an additional 400 kg P/ha was applied in year 5 with the ROI for years 5 to 7 being the average ROI of years 1 to 4; for the 1000 kg P/ha rate there was no reapplication of the fertiliser(s). Note the total percentage ROI for each fertiliser application rate is the sum of the applicable column.

		Application rate (kg P/ha)			
Fertiliser	Year	100	200	400	1,000
RPR	1	-100	203	54	-14
	2	542	506	327	114
	3	-100	808	541	221
	4	542	203	755	328
	5	-100	506	419	435
	6	542	808	419	543
	7	221	506	419	650
	Total	1,548	3,539	2,936	2,278
BioPhos	1	-100	275	92	8
	2	690	651	432	167
	3	-100	1,026	698	301
	4	690	275	964	434
	5	-100	651	546	568
	6	690	1,026	546	701
	7	295	651	546	835
	Total	2,065	4,554	3,825	3,014
BioSuper	1	518	291	187	66
	2	1,135	814	561	260
	3	518	1,271	892	439
	4	1,135	291	1,222	619
	5	518	814	715	799
	6	1,135	1,271	715	979
	7	826	792	715	1,158
	Total	5,785	5,544	5,008	4,320

5.3.3 DISCUSSION

As it stands, the BioPhos product currently on the market is reported to have a lower P concentration than the BioPhos that was used in these studies (11.0 % c.f. 14.1 % w/w, respectively). Because of uncertainties around differences in reactivity etc it is therefore difficult to know how the BioPhos currently available would compare economically against the product(s) being tested here.

The soil used in the present study has a relatively low P-retention value (34 %; Table 3.2) suggesting that a reasonable proportion of the P released will remain available to plants over the short to medium term. The $Log_{(3)}$ correction (Equation 8) undertaken to account for the negative effect that increasing time has on Bic-P was speculative but without it, the assumption would be that all of the P released from the fertilisers would remain plant-available indefinitely. Thus assuming 25 kg P/ha/year is removed by the crop, 1,000 kg P/ha would maintain production for ca. 40 years (1,000/50); clearly, this is not realistic. Moreover, Equation 8 needs testing in order to validate it under various soil and environmental conditions.

The potential yield of the crop plays a major role in determining crop response to applied-P, as does the initial amount of plant-available P. Lower potential yields produce lower yield responses to a given increase in Bic-P, whilst higher potential yields have a relatively higher yield response (Appendix 1). The yield response and economic analysis presented above are relative to the assumptions made; i.e. that Bic-P is 8.5 µg/g, and the P response curve used (Appendix 1; P_{yld68}), which states that that potential yield at this Olsen P concentration is ca. 55 t/ha. Alterations to these assumptions will require that the data be reanalysed. For example lower Olsen P concentrations or higher potential yields (brought about through irrigation and/or enhanced N supply) will increase the yield and economic response and vice versa. Likewise, increased fertiliser or transport costs would reduce the economic response whilst increasing price for potatoes would increase it.

5.4 Differences in ΔBic-P between laboratory and field studies

There were marked differences between the laboratory and field studies in the changes in Bic-P over time. These differences were thought to be the result of a number of uncontrolled yet quantifiable factors including soil pH, aggregate size distribution (which affects the fertiliser/soil contact surface area or fertiliser dilution), moisture, temperature and others (e.g. uniformity of mixing the fertilisers with the soil). Most of these factors have been mentioned and results presented where

appropriate in Chapter 3 and Chapter 4. This section attempts to explain the differences in Bic-P between the laboratory and field studies by quantifying the effects of some of these factors.

5.4.1 SOIL PH

Although the soil pH at the start of the laboratory and field studies was the same (i.e. 5.6 units), there were marked differences between the two studies in soil pH fluxes over time. Soil pH in the laboratory study fell markedly over the 155 day incubation period in all treatments including the Control. This was largely put down to nitrification. In the field study, soil pH was relatively stable over a 344 day period in all treatments where pH was measured except for BioSuper (678 mg P/kg soil) where it fell markedly. BioSuper also reduced soil pH below that of the Control in the laboratory study, and in both studies this was the result of oxidation of the S^o contained in this fertiliser by soil micro-organisms.

Changes in plant-available P concentrations as a result of PR application are strongly related to soil pH (see section 2.2.2). Two studies were found that investigated the effects of soil pH on ΔBic-P (Kanabo and Gilkes, 1987b; Rajan et al., 1991a). Kanabo and Gilkes (1987b) found a negative linear relationship between log Bic-P and soil pH:

Equation 9.

$$Log\ \Delta Bic\text{-}P = c - d.pH$$

where *d* ranged from -0.39 to -0.40 for incubation periods of 1 to 7 days respectively (mean -0.395) and c from 3.15 to 3.16 (mean 3.155). Similar values for *d* were apparent over a range of PR application rates (200 to 1600 mg P/kg soil).

Results from Rajan et al., (1991a) were similar to those of Kanabo and Gilkes (1987b) except that data were collected over a 3 year time frame; but no equation describing the results was presented. However, data from years two and three in Rajan et al.,

(1991a) were pooled because they behaved similarly and parameters fitting Equation 9 were generated in a spreadsheet. The slope (*d*) of the Log_{10} data from Rajan et al., (1991a) was -0.182 (R^2 = 0.74) and *c* was 2.309.

Using the relationship in Equation 9 and the slopes from Kanabo and Gilkes (1987b) and Rajan et al., (1991a) mentioned above, the effects of soil pH on the differences in ΔBic-P between the laboratory and field studies were estimated. To do this the Control was used as the 'case study' treatment and only the 0 to 155 DAFA period of the field study data used. Note that differences in soil pH between PR fertiliser treatments across the laboratory and field studies could not be elucidated easily because there was no 678 mg P/kg soil application rate in the laboratory study (doing this would have required another set of interpolated models to be generated based on the laboratory data).

The changes in soil pH in the laboratory Control treatment were described well by a negative exponential relationship (pH = A+B/(1+D*X)); where X equals DAFA and A, B and D equal 4.83, 0.91 and 0.0247 respectively (P <0.001; R^2 = 0.81). In the field experiment the pH flux of the Control treatment was not so well described by the relationship (pH = A+(B+C*X)*(R^X)); where X equals DAFA and R, B, C and A equal 0.9768, -0.176, 0.0903 and 5.8217 respectively (P = 0.083; R^2 = 0.16); but when replicates were set as groups with common *R*, *B* and *C* values (0.3697, -0.214 and -3578 respectively) the significance and R^2 were significantly improved (P = 0.016; R^2 = 0.49).[17] Integration of these models produced average pH values for each experiment that were used instead of a full integration, to simplify the analysis. Full integration of the changes in soil pH over time is not warranted as the relevance of Equation 9 to the present studies is questionable (e.g. differences in experimental conditions, soil and PR type, incubation period etc).

Based on these models average pH in the laboratory experiment was 5.2 units whereas in the field experiment it was 5.9 units.

[17] The significance of the change was P = 0.034

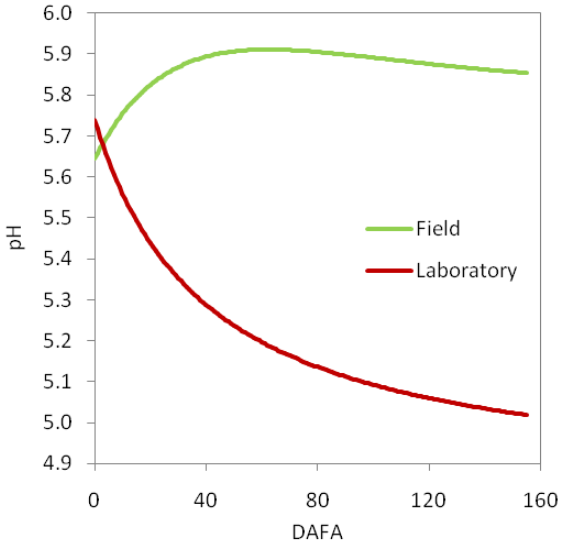


Figure 5.6. Comparison between the modelled changes in pH over time (DAFA; days after fertiliser application) of the Control treatments in the field and laboratory studies. See text for details of models used for generation of the curves.

Solving of Equation 9 using the parameters presented above from Kanabo and Gilkes (1987b) and Rajan et al. (1991a) gave almost identical answers for the expected difference in ΔBic-P between the laboratory and field studies over a 155 DAFA period (5.86 and 5.94 µg/g respectively) for the Control treatment.

The differences in Bic-P between the laboratory and field studies at 155 DAFA for RPR/BioPhos and BioSuper applied at 678 mg P/kg soil were 10.2 and 9.6 µg/g respectively (Figure 5.3). Thus, if it is assumed that within fertiliser treatments the relativities in soil pH between the laboratory and field studies were similar to that of the respective Control treatments, then differences in soil pH explained around 50 % of the difference in ΔBic-P between the laboratory and field studies.

5.4.2 SOIL AGGREGATE SIZE DISTRIBUTION

The soil used in the laboratory study was passed through a 2 mm sieve prior to incubation, whereas the field study used a cultivated soil with a wide range of aggregate sizes. Thus there were expected to be marked differences in the specific surface area (SA; m^2/kg soil) of the soils in the two studies.

The SA of the soil was calculated using the data presented in Figure 5.7 and the proportion of the total mass of soil in each aggregate size class (Table 3.2 and Figure 4.3). Aggregate volume and SA calculations were based on that of a sphere (where the radius equals the average of the upper and lower mesh size of each aggregate size fraction divided by two). The density of the >2 mm aggregates was based on weighed aggregates (n = 100), whereas the <2 mm fraction was assumed to have the same aggregate density as the average of the >2 mm fractions (1.52 g/ml).[18] Thus, the (potential contact) SA of the soil used in the laboratory study was 11.1 m^2/kg, whereas in the field study it was 4.8 m^2/kg.

Fertilisers were put through a 250 µm sieve in both studies which minimised differences in SA among the fertilisers; although application of the method of determining soil SA (above) indicated that RPR and BioPhos had slightly different specific SA's (24.5 and 29.6 m^2/kg respectively).[19]

Using the relationship between fertiliser application rate and soil SA, the difference between the laboratory and field studies in P applied per unit of SA (P-saturation; P_{sat}; mg P/m^2) was calculated.[20] At the 678 mg P/kg soil application rate, P_{sat} in the field study was 141 mg P/m^2 whereas P_{sat} in the laboratory study was 61 mg P/m^2. Respective Bic-P values for RPR/BioPhos for the field and laboratory studies at 155 DAFA were 2.4 and 12.6 µg/g and for BioSuper they were 7.3 and 16.9 µg/g (Figure 5.3). However, the relationship between P_{sat} and ΔBic-P must be related to application

[18] Note, there was no relationship between aggregate size and aggregate density for the >2 mm fraction; slope = 0 (data not shown).
[19] The calculation of specific surface area included average and assumed values for some variables so the statistical significance of these differences was not assessed.
[20] Assuming perfect soil/fertiliser mixing uniformity in both the laboratory and studies.

rate in order to be useful. This relationship was generated using the range of RPR application rates from in the laboratory study (Figure 5.8). It shows that at a P_{sat} of 61 g P/kg soil (i.e. 678 mg P/kg soil in the laboratory study) the increase in Bic-P is 19.7 µg/g; and when P_{sat} is at 141 g P/kg soil (i.e. 678 mg P/kg soil in the field study) the increase in Bic-P is 9.5 µg/g. Thus it appears as though P_{sat} accounts for ca. 50 % of the difference (9.5/19.7) in ΔBic-P between the field and laboratory studies.

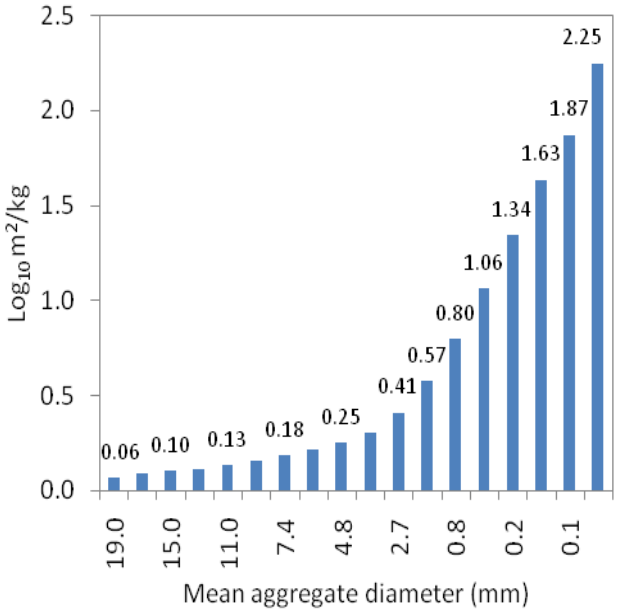


Figure 5.7. Surface area per kg soil (m^2/kg soil) for various sized soil aggregates. Note the Log_{10} (+1) scale on the *y-axis*. Data labels are also the Log_{10} (+1) of the aggregate surface area. The laboratory study included only the <2mm diameter aggregates (11.1 m^2/kg soil) whilst the field study had the full range of aggregates from 19 mm to <0.5mm (4.8 m^2/kg soil).

Furthermore, differences in the uniformity of mixing of the fertilisers with the soil may also have affected the results but this was not measured. It is likely that mixing would have been less uniform in the field study, leading to less dissolution compared with the laboratory study.

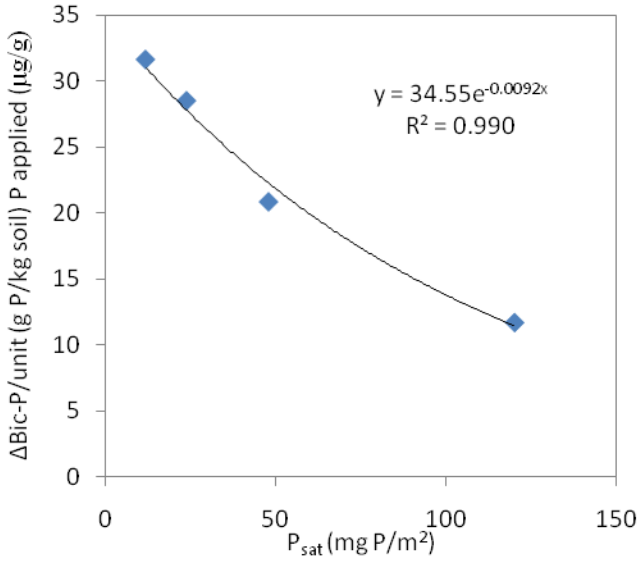


Figure 5.8. The relationship between the change in Bic-P (ΔBic-P; µg/g) per unit of P applied (g P/kg soil) and P-saturation (P_{sat}; mg P/m^2 soil surface area) from the laboratory study.

5.4.3 SOIL MOISTURE

As mentioned in section 2.2.4 increasing soil moisture increases PR dissolution rate; up to the point of field capacity after which soil moisture has little effect. The laboratory study had constant soil MC of 40.0 % w/w (or 32.7 % v/v; Table 3.2).

Changes in the soil MC over the season in the field study was estimated using the Potato Calculator (Jamieson et al., 2006) (Figure 5.9). Mean soil MC in the top 10 cm of soil over the growing season was 30.7 % (w/w). Equation 10 (Kanabo and Gilkes, 1988b) suggests that the difference in the rate of change in Bic-P between 20 and 30 % MC (as it was most of the time in the field study over the crop growth period) was minimal. Furthermore, soil MC % in the top 10 cm of the soil profile over the winter months would have been well above the 25 % w/w maximum dissolution threshold most of the time.

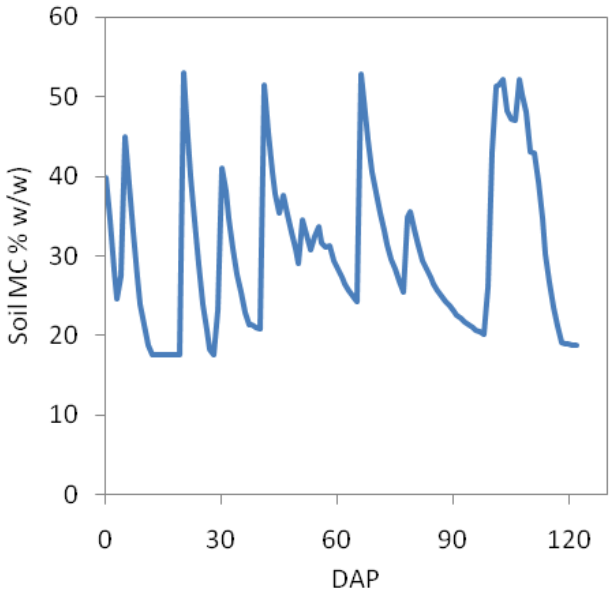


Figure 5.9. Soil moisture content (% w/w) fluxes over the (potato) growing season (2004-05) in the top 10 cm of the soil profile of the field study; simulated using the Potato Calculator (Jamieson et al., 2006). DAP = days after planting.

Equation 10.

$$\Delta\text{Bic-P} = A - B \exp(-CW)$$

where W = soil water content (% w/w); A = the asymptote; B a constant and C the curvature coefficient.

Although the effects of soil MC on differences in ΔBic-P in the laboratory and field studies cannot be entirely excluded, differences in soil MC probably did not have a major impact on the differences in apparent dissolution and subsequent changes in Bic-P in the laboratory and field studies.

5.4.4 Soil temperature

Temperature is a key factor governing the rate of many chemical and biological transformations. Soil temperature in the laboratory study was 15^{o}C, whereas mean soil temperature over the crop growth period in the fertiliser incorporation zone in the field study was 18.4^{o}C ($^{+}$/$_{-}$ 2.4). Mean temperature in the field study was within 0.5^{o}C of 15^{o}C of the laboratory study on 15 days over the (125 day) crop growth period; within

1.0^{o}C for 30 days, and within 2.0^{o}C for 87 days. Soil temperature was < 15^{o}C (mean 13.4^{o}C) on 35 days.

The work of Kirk and Nye (1986a), Watkinson (1994b), Gillard et al. (1997), and Smalberger et al. (2006) suggests that temperature is not an important variable affecting dissolution because these PR models/DSS's do not include temperature as a variable. Evans et al. (2006) found that at an application rate of 70 kg P/ha a 10^{o}C increase from 10 to 20^{o}C (which covers the bulk of the data spread from the field study) yielded an additional Bic-P flux of +3.2 μg/g (up from about 16 μg/g)[21] after a 30 day period at field capacity. Because the field experiment had a mean daily temperature over the cropping period 3.4^{o}C greater than the laboratory study, yet the laboratory study had larger Bic-P fluxes, temperature is clearly not helping explain the differences in Bic-P between the field and laboratory studies. Thus if temperature did play a role, it was in favour of the field experiment and clearly offset by other factors such as those described above.

5.5 SUMMARY

One of the aims of this chapter was to estimate the optimum economic application rate for each fertiliser. However, because there were anomalies in the shape of the ΔBic-P curves in the laboratory study, these were smoothed. Also, because these same curves only described the changes in Bic-P over a 155 day period they were stretched along the *x*-axis so that they spanned the period of time that the field study ran for (344 days). These laboratory curves were then calibrated so that they lay on top of the field curves. From here a full suite of curves was generated for each fertiliser for field conditions. However, because the curve at the lowest application rate (67 mg P/kg soil) described the data poorly, this rate was left out of the subsequent P-response modelling exercise and economic analyses.

The smoothed calibrated curves were used to estimate optimum economic application rate for each fertiliser using the nutrient response model PARJIB (Reid, 2002). The

[21] This is an assumed value from other data in the Evans et al. (2006) study.

response to applied P was based on an initial soil Olsen P of 8.5 µg/g. Fertilisers were assumed to be applied 6 months before planting potatoes. Potential yield was set at 68 t/ha (i.e. the potential yield of potatoes when seasonal rainfall was ca. the long-term average for the season), which resulted in a simulated yield of 54 t/ha at an Olsen P of 8.5 µg/g. The price of potatoes was set at $1,000 /t and a 100 % pack-out was assumed.

Higher application rates would require less frequent application but the decline in frequency was not proportional to the application rate. Because no relevant information was found in the literature on the persistence of PR in cropping soils and the decline in yield as the plant-available P begins to fall with time (as a result of P uptake and other losses) an estimation was made on the amount of time required between subsequent fertiliser applications at each fertiliser application rate (Equation 8.). The resulting yield response data indicated that the optimum economic application rate for BioSuper was 100 kg P/ha, and that this may need to be applied every second year. For RPR and BioPhos the optimum economic application rate was 200 kg P/ha and that this may need to be reapplied every third year. In both cases the fertilisers should be applied at least six months before planting.

The other main aim of this chapter was to explain why the ΔBic-P curves differed so greatly between the laboratory and field studies. In the laboratory study soil pH fell markedly over the incubation period (155 DAFA) whereas in the field study soil pH remained relatively constant. Using empirical relationships found in the literature, differences in soil pH between the two studies accounted for ca. 50 % of the differences in Bic-P fluxes. Furthermore, there were marked differences in the specific surface area of the soil between the two studies. In the laboratory study fertilisers were applied to a sieved (<2 mm) soil; smaller aggregates have a larger surface area. In the field study, fertilisers were applied to a cultivated soil with much larger aggregates; larger aggregates have a smaller specific surface area. By calculating the specific surface area of the sols in both studies as well as the relationship between fertiliser application rate and the soil surface area (P_{sat}) in the laboratory study and the P_{sat} in

the field study, indications were that differences in P_{sat} also explained ca. 50 % of the difference in Bic-P fluxes between the two studies.

Soil moisture and temperature were also investigated but the effects of these were smaller and may have cancelled each other out, because higher soil temperatures in the field study would theoretically increase PR dissolution and slightly lower moisture in the field study would theoretically retard PR dissolution; although the effects of soil moisture may have been far smaller than those of soil temperature.

CHAPTER 6

6 SUMMARY AND CONCLUSIONS

Prior to the onset of this study a survey was undertaken to identify the limitations to production facing the ECOPT. This survey highlighted that most growers are experiencing a range of production limitations. In order to boost production, an integrated approach to nutrient, weed, and pest and disease management is required if the ECOPT growers are serious about increasing their crop yields. Furthermore, irrigation may help further increase production, but will be most effective once systems have been developed and implemented to overcome these other limitations.

A common thread for virtually all growers was low soil plant-available P (Olsen P) concentration, which averaged ca. 6 μg P/l soil. Thus, economically increasing Olsen P levels was considered fundamental to increasing production levels.

The primary objective of this research was to identify the optimum economic application rate of a range of organically approved P fertilisers to help growers of the ECOPT increase production levels. Although a longer study period would have been beneficial to achieving the objectives; a four-step approach over a one year period was used:

i) A laboratory experiment (Chapter 3) using various fertilisers at different application rates was conducted to determine suitable rates for a field study and to produce a suite of models of PR dissolution and changes in Bic-P that would be calibrated for field conditions.

ii) A field study (Chapter 4) was undertaken using the same fertilisers as the laboratory study but at rates deemed suitable[22] from the laboratory study. Data on changes in Bic-P were collected so that models for changes in Bic-P could be used to calibrate the laboratory ΔBic-P models. Soil pH, soil

[22] Provide the biggest increases in Bic-P and the best chance of detecting a P response from the test crop.

moisture and soil temperature data were also collected to help explain any variation in the ΔBic-P models from the two studies. Potatoes were used as a test crop.

iii) Integration of the ΔBic-P models from the laboratory and field studies was done to calibrate the laboratory study models for field conditions. These calibrated models were then used to provide data on the expected changes in Bic-P in the field for a range of application rates.

iv) Modelling and subsequent economic analysis using the data obtained from the calibrated curves and PARJIB simulations enabled the identification of optimum economic application rates for each fertiliser.

The soil type used in the laboratory and field studies was a Hikuwai fine sandy loam, an alluvial soil located on an intermediate terrace of the Waiapu river and was considered similar to the type of soil used by a number of ECOPT growers. The location of the field study was Tikapa, approximately 15 km North East of Ruatoria, Eastland (Gisborne region), New Zealand.

The laboratory study indicated that application rate has a profound effect on PR dissolution and Bic-P fluxes. Increasing application rate increased the absolute amount of P dissolved from the PRs and the subsequent increase in Bic-P but decreased the proportion of applied P that dissolved.

BioSuper at the highest application rate tested in the laboratory study (1,333 mg P/kg soil) significantly decreased soil pH (relative to the Control) but only after 57 DAFA, whereas RPR and BioPhos did not affect soil pH significantly. In the field study BioSuper (applied at 678 mg P/kg soil) also decreased soil pH, but again only after 57 DAFA. This indicates that there is a lengthy lag period between application of BioSuper and any significant decrease in soil pH.

Beneficiation may enhance PR dissolution and plant-available P but this depends on the system used. Of the two beneficiated fertilisers used in this research, BioSuper was

superior but this may be affected by application rate. For example, percentage dissolution (measured only in the laboratory study) of BioSuper was significantly greater than BioPhos (when applied at 267 mg P/kg soil) at three and 22 DAFA, but there were no significant differences between these two treatments on other sampling dates or at the higher application rate (1,333 mg P/kg soil).

Changes in Bic-P were measured in both the laboratory and field studies. Data showed that Bic-P increased with increasing application rate and time, and that BioSuper had much higher increases in Bic-P at equivalent application rates than BioPhos and RPR, which were generally not significantly different. Approximately 1 year (344 days) after fertiliser application, the changes in Bic-P that could be expected are around 2.5, 3.8 and 11.0 μg/g for RPR, BioPhos and BioSuper respectively, if applied at ca. 488 kg P/ha (678 mg P/kg soil). However, the decrease in the changes in Bic-P at lower application rates is not linear such that a 50 % decrease in application rate may result in a much smaller reduction in ΔBic-P.

The increase in Olsen P resulting from PR dissolution is directly related to the amount of P dissolved, for BioPhos and RPR, but not BioSuper. The laboratory study showed that the unit increase in Bic-P per unit of P dissolved from BioPhos was more than RPR (0.153 vs. 0.05 μg/g/mg/kg respectively; Figure 3.6). There was no clear relationship for BioSuper (R^2 = 0.37). There were also no studies found in the literature describing the relationship between Bic-P and dissolution of BioSuper so the reason for the markedly poorer relationship for this fertiliser is unknown.

This study further demonstrated that PR dissolution is affected by both environmental and management factors, including soil pH, application rate and dilution in the soil. Although this research was not designed specifically to test the effects of soil pH, soil moisture or dilution on the relative performance of the fertilisers being tested, differences in these (uncontrolled) variables helped explain a large proportion of the variability in the changes in Bic-P witnessed between the laboratory and field studies. Soil pH explained ca. 50 % of the variation in Bic-P between these two studies at 155 DAFA, whilst P_{sat} (a measure of the ratio between the amount of P applied and the

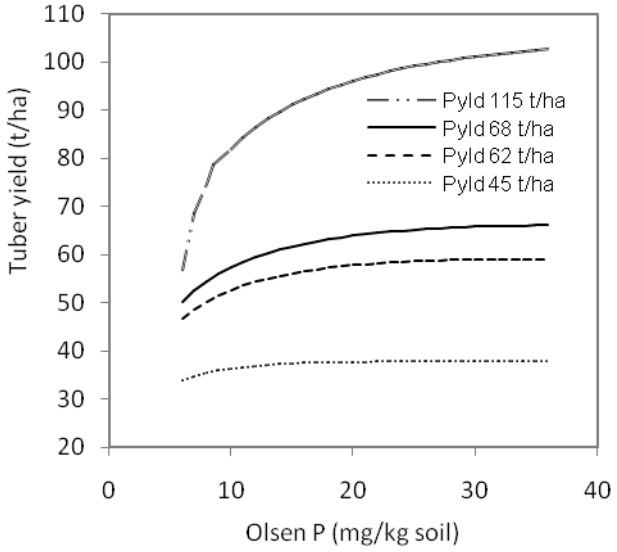
surface area of the soil; mg P/m^2) explained another 50 %. Variation between the two studies in mean soil temperature and soil moisture worked out in favour of the field study, with the field study being slightly moister (30.7 % w/w) and warmer (18.4^oC) over the cropping period than the laboratory study (28.6 % and 15^oC respectively).

The crop nutrient response modelling exercise and subsequent economic analysis suggests that the optimum economic application rate for BioSuper is 100 kg P/ha (applied every two years) and for RPR and BioPhos, 200 kg P/ha (applied every three years). The underlying assumptions for these results were that the fertilisers were applied 6 months before planting; potatoes were the crop grown; the price for potatoes was $1,000 /t (at the farm gate); the cost of the fertilisers were relevant at the time of preparing this document (see Table 5.3); and that the fertilisers would need to be re-applied at a frequency dependant on application rate (2 years at 100 kg P/ha; 3 years at 200 kg P/ha; 4 years at 400 kg P/ha and 7 years at 1,000 kg P/ha). Clearly, if any of these assumptions change the exercise would need to be repeated to check if these conclusions remain valid. In the case of the "times to reapplication" the model that was used to generate them clearly needs to be tested in the field.

Finally, it must be understood that without an integrated approach aimed at addressing the other barriers to production as well, increasing the Olsen P concentration by itself through application of PR fertiliser will have little benefit. For example, applying PR may encourage weed growth which in turn puts pressure on the amount of N and water available to the crop. On sites with very low Olsen P concentrations it may be worth considering growing crops more tolerant of low P-availability (e.g. maize), or those which can more utilise P more effectively from PR (such as legumes, rape, kale or buckwheat) until Olsen P concentrations can be increased substantially, which the results from this study suggest will take at least a year.

7 APPENDICES

APPENDIX 1



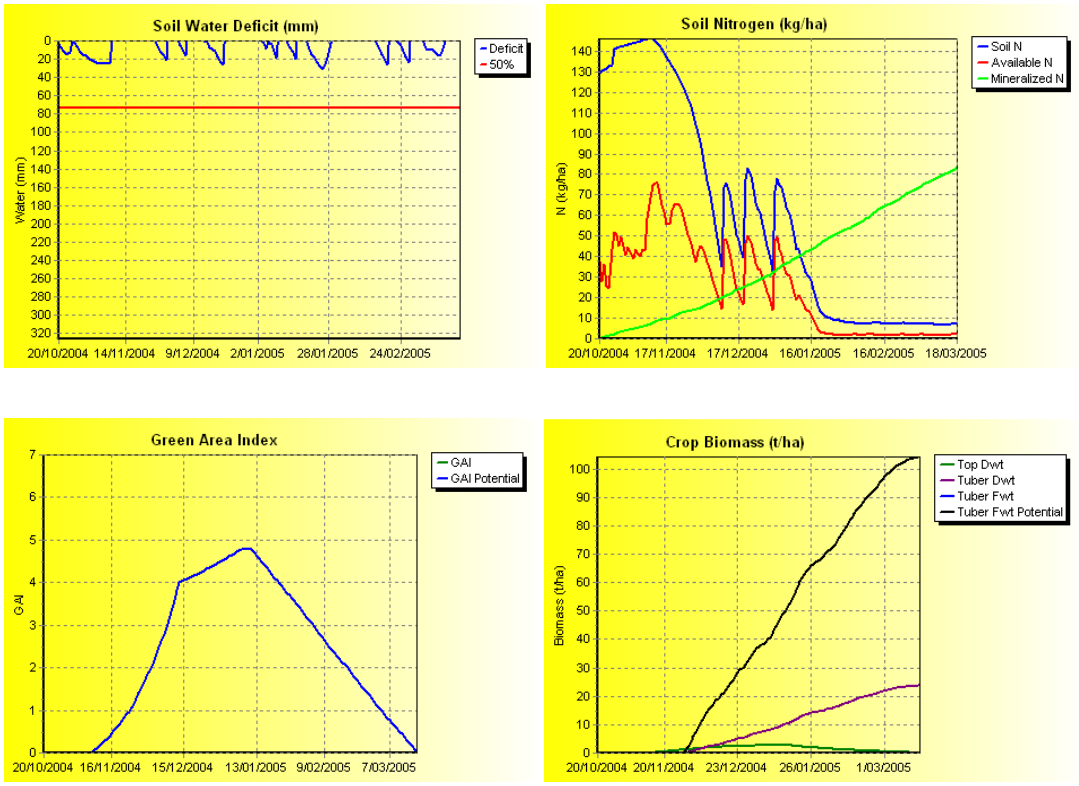
PARJIB potato tuber yield response to Olsen P (Reid, 2002). P_{yld} = potential yield.

These P-response curves were generated in the fertiliser response model PARJIB (Reid, 2002), by setting the potential yield (P_{yld}) parameter to 45, 62, 68 and 115 t/ha (assuming tubers were 20 % DM). The model generates a P response curve that asymptotes at the inputted potential yield. The maximum Olsen P used in the simulations was 36 µg/g. At a potential yield of 100 t/ha the curve asymptotes at an Olsen p of 65 µg/g. Therefore, most of the curves presented above have not reached their set potential yield at an Olsen P of 36 µg/g.

When P_{yld} was 45 t/ha the simulated yield when Olsen P was 8.5 µg/g, was 35 t/ha (the same yield that was achieved in the field study). When P_{yld} was 62 t/ha the simulated yield when Olsen P was 8.5 µg/g, was 51 t/ha (which was the potential yield estimate from the Potato calculator run using the weather and soil data from Table 4.3 and Table 4.2 respectively, with no irrigation or N fertiliser; Figure 4.12; section 4.5). When P_{yld} was 68 t/ha (the potential yield from the Potato Calculator when total monthly rainfall was average; Appendix 3) the simulated yield when Olsen P was 8.5 µg/g, was

55.4 t/ha. When P_{yld} was 115 t/ha (the simulated yield at an Olsen P of 36 µg/g was 104 t/ha which was the same as the maximum simulated yield from the Potato Calculator when water and N were non-limiting, or applied to meet crop demands; Appendix 2) the simulated yield when Olsen P was 8.5 µg/g, was 76.8 t/ha. This latter curve (P_{yld} = 115 t/ha) indicates that large yield increases can be achieved with small increases in Olsen P (particularly at the lower end of the response curve), providing the crops water and N demands is met.

Appendix 2



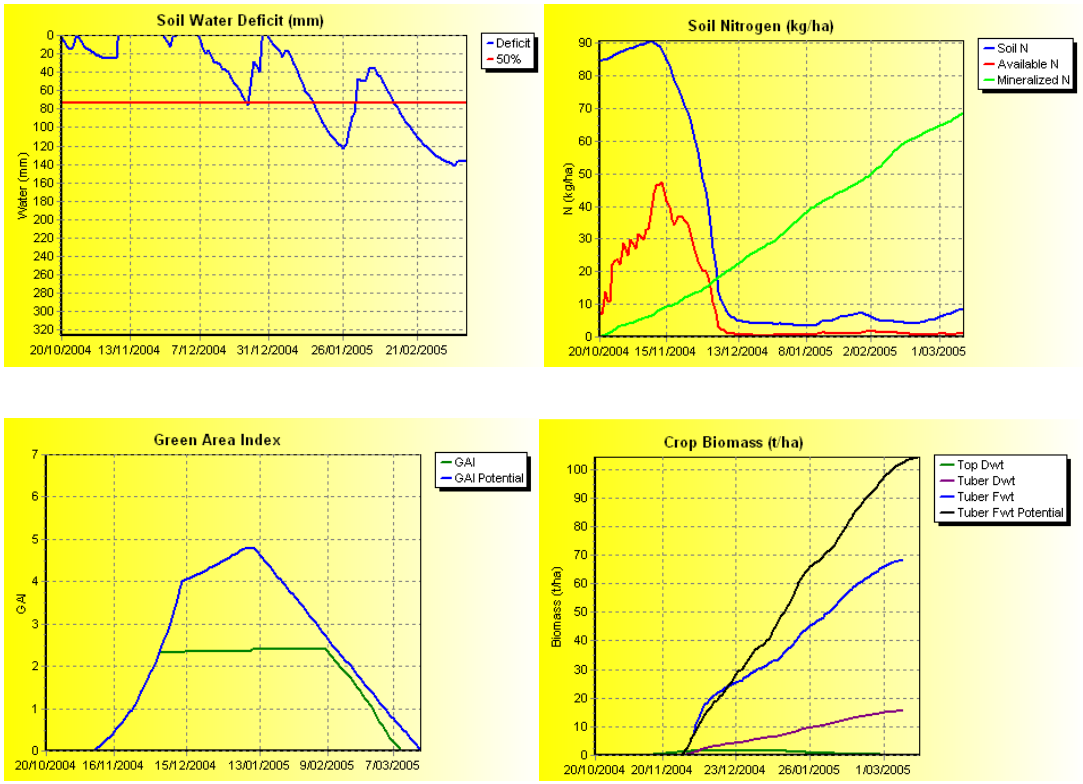
Simulated SWD, soil nitrogen, GAI and crop yield/biomass figures from the Potato Calculator (Jamieson et al., 2006) for a hypothetical potato crop grown using the same constraint (maximum GAI = 4.5) and soil and weather data as the simulation in Figure 4.12 (section 4.5) but with irrigation and N supplied to meet crop demands.

These simulation outputs are from the Potato Calculator (Jamieson et al., 2006) and were undertaken using the soil data from Table 4.2 and weather data from Table 4.3, and with irrigation and nitrogen applied to meet crop demands, so that they are not limiting. The Potato calculator assumes that P is not limiting production.

Compared with Figure 4.12 (section 4.5), SWD and soil nitrogen levels were far more optimal, meaning that maximum potential GAI development and maintenance, and yield and biomass accumulation were achieved. In this case the simulated yield at final harvest was 104 t/ha. Full canopy senescence date was 21 March 2005, and 320 kg N/ha (four 60 kg N/ha applications) and 250 mm of irrigation (five 50 mm applications) were applied.

The P_{yld} = 115 t/ha P response curve in Appendix 1 indicates that when Olsen P was 8.5 µg/g potato yield was 77 t/ha. Therefore the yield difference between 8.5 µg/g and the optimum Olsen P level (>35 µg/g; as assumed in the Potato Calculator; 104 t/ha, as simulated above) was ca. 27 t/ha.

Appendix 3



Simulated SWD, soil nitrogen, GAI and crop yield/biomass figures from the Potato Calculator (Jamieson et al., 2006) for a hypothetical potato crop grown using the same constraints and soil and weather data as the Potato Calculator simulation in Chapter 4 (section 4.5) but with total monthly rainfall adjusted to equal average monthly rainfall (Figure 4.1).

These simulation outputs are from the Potato Calculator (Jamieson et al., 2006) and were undertaken using the soil data from Table 4.2 and weather data from Table 4.3, but with total monthly rainfall adjusted to equal the average monthly rainfall for the area (Figure 4.1). This rainfall adjustment was done by applying 21 mm of irrigation on 1 December 2004, 58 mm on 1 January 2005 and 6 mm on 1 February 2005. The Potato calculator assumes that P is not limiting production.

Compared with Figure 4.12 (section 4.5) the maintenance of GAI and tuber growth was much more sustained over the season, although still short of that if water and N were applied to meet crop demands (Appendix 2). Simulated yield was 68.4 t/ha and full canopy senescence was on 13 March 2005. Using PARJIB to account for lower than

optimal Olsen P, when Olsen P was 8.5 the potential yield was 55.4 t/ha (see Appendix 1).

REFERENCES

Agbenin, J.O. 2004. Free energy and kinetics of dissolution of Sokoto rock phosphate and the implications for replenishing phosphorus in the savanna soil of Nigeria. European Journal of Soil Science 55:55-61.

Allison, M.F., J.H. Fowler, and E.J. Allen. 2001. Effects of soil- and foliar-applied phosphorus fertilizers on the potato (*Solanum tuberosum*) crop. Journal of Agricultural Science 137:379-395.

Anon. 1983. Phosphorus (Routine spectrophotometric method) Analytical Methods for Fertiliser Materials. NZ Fertiliser Manufacturer's Association Auckland, New Zealand.

Arcand, M.M., and K.D. Schneider. 2006. Plant- and microbial-based mechanisms to improve the agronomic effectiveness of phosphate rock: a review. Anais Da Academia Brasileira De Ciencias 78:791-807.

Ashcroft, W., A. Surapaneni, and A. Milner. 2004. Response of processing tomatoes to an alternative phosphate fertiliser incorporating composted fish waste. 6th World congress on the processing tomato and 9th ISHS symposium on the processing tomato. 6:15-18.

Babare, A.M., R.J. Gilkes, and P.W.G. Sale. 1997. The effect of phosphate buffering capacity and other soil properties on North Carolina phosphate rock dissolution, availability of dissolved phosphorus and relative agronomic effectiveness. Australian Journal of Experimental Agriculture 37:1037-1049.

Barnes, J.S., and E.J. Kamprath. 1975. Availability of North Carolina rock phosphate applied to soils. 23 pp. Technical Bulletin 229, North Carolina Agricultural Experiment Station. Raleigh, North Carolina State University.

Barreto, W.O., J.L. dePaula, and M.N. Duarte. 1997. Manual de Métodos de Análise de Solos. EMBRAPA, Brasília.

Barrow, N.J., and T.C. Shaw. 1976. Sodium bicarbonate as an extractant for soil phosphate. I. Separation of the factors affecting the amount of phosphate displaced from soil from those affecting secondary adsorption. Geoderma 16:91-107.

Bascomb, C.L. 1964. Rapid method for the determination of cation exchange capacity of calcareous and non-calcareous soils. Journal of the Science of Food and Agriculture 15:351-362.

Bingham, F.T. 1966. Chapter 23. Phosphorus, p. 310-323, *In* H. D. Chapman, ed. Diagnostic criteria for plants & soils. University of California. Divison of Agricultural Sciences. Riverside, California.

BioGro. 2008. BioGro Certification Standards [Online]. Available by BioGro New Zealand http://www.biogro.co.nz/main.php?page=170 (verified August 2008).

Blakemore, L.C., P.L. Searle, and B.K. Daly. 1987. Methods for chemical analysis of soils. New Zealand DSIR. New Zealand Soil Bureau Scientific Report 80.

Bolan, N.S., and M.J. Hedley. 1989. Dissolution of phosphate rocks in soils .1. Evaluation of extraction methods for the measurement of phosphate rock dissolution. Fertilizer Research 19:65-75.

Bolan, N.S., J. Elliott, P.E.H. Gregg, and S. Weil. 1997. Enhanced dissolution of phosphate rocks in the rhizosphere. Biology and Fertility of Soils 24:169-174.

Bolland, M.D.A. 1995. Yield response of subterranean clover to applications of superphosphate and rock phosphate measured in the year of application at the same site in different years. Journal of Plant Nutrition 18:47-63.

Bolland, M.D.A., and R.J. Gilkes. 1997. The agronomic effectiveness of reactive phosphate rocks. 2. Effect of phosphate rock reactivity. Australian Journal of Experimental Agriculture 37:937-946.

Burton, W.G. 1989. The Potato. 3rd ed. Longman Scientific & Technical, Singapore.

Chitralekha, R., S.S.S. Rajan, and C.D.A. McLay. 2002. Influence of superphosphate and microbial phosphate fertilisers on absorbed and solution P in allophonic soil. [Online] http://www.gardenews.co.nz/BioPhos%20Booklet.pdf (verified 2-May-2008).

Clarke, C.J., G.S. Smith, M. Prasad, and I.S. Cornforth. 1986. Fertiliser recommendations for horticultural crops Ministry of Agriculture and Fisheries, Wellington.

Craighead, M.D. 2004. Phosphate sources for pasture production on summer-dry soils in eastern New Zealand. New Zealand Journal of Agricultural Research 47:179-190.

Cunniff, P. 1999. Official Methods of Analysis of AOAC International 18th ed. Official method 1985.01. Association of Official Analytical Chemists International. Washington DC.

Dodor, D.E., K. Oya, Y. Tokashiki, and M. Shimo. 1999. Dissolution of phosphate rock fertilisers in some soils of Okinawa, Japan. Australian Journal of Soil Research 37:115-122.

Evans, J., L. McDonald, and A. Price. 2006. Application of reactive phosphate rock and sulphur fertilisers to enhance the availability of soil phosphate in organic farming. Nutrient Cycling in Agroecosystems 75:233-246.

Fisher, M.J. 1980. The influence of water stress on nitrogen and phosphorus uptake and concentrations in Townsville stylo (*Stylosanthes humilis*). Australian Journal of Experimental Agriculture and Animal Husbandry 20:175-180.

Gahoonia, T.S., D. Care, and N.E. Nielsen. 1997. Root hairs and phosphorus acquisition of wheat and barley cultivars. Plant and Soil 191:181-188.

Garden, D.L., G.N. Ward, P.W.G. Sale, S. Tennakoon, R.P. Hindell, and B. Gardiner. 1997. The agronomic effectiveness of reactive phosphate rocks 3. A comparison of application strategies for soluble phosphorus and reactive phosphate rock fertilisers. Australian Journal of Experimental Agriculture 37:947-956.

Gerke, J., U. Meyer, and W. Romer. 1995. Phosphate, Fe and Mn uptake of N_2 fixing red clover and ryegrass from an Oxisol as affected by P and model humic substances application. 1. Plant parameters and soil solution composition. Zeitschrift fur Pflanzenernahrung und Bodenkunde 158:261-268.

Ghani, A., and S.S.S. Rajan. 1995. Low cost method for producing biologically acidulated phosphate rocks: a suitable phosphorus and sulphur fertilizer for organic and conventional farming. Agro-Chemicals News in Brief 18:4-7.

Ghani, A., S.S.S. Rajan, and A. Lee. 1994. Enhancement of phosphate rock solubility through biological processes. Soil Biology & Biochemistry 26:127-136.

Gillard, P., P.W.G. Sale, and S.B. Tennakoon. 1997. Building an expert system to advise on the use of reactive phosphate rock on Australian pastures. Australian Journal of Experimental Agriculture 37:1077-1084.

Goldspink, B.H., and K.M. Howes. 2000. Fertilisers for wine grapes : an information package to promote efficient fertiliser practices. Agriculture Western Australia. South Perth, WA.

Hamalova, M., J. Hodslavska, P. Janos, and V. Kanicky. 1997. Determination of phosphorus, potassium, and magnesium in fertilizers by inductively coupled plasma-atomic emission spectroscopy and comparison with other techniques. Journal of AOAC International 80:1151-1155.

Hart, M.R., B.F. Quin, and M.L. Nguyen. 2004. Phosphorus runoff from agricultural land and direct fertilizer effects: A review. Journal of Environmental Quality 33:1954-1972.

Haynes, R.J. 1992. Relative ability of a range of crop species to use phosphate rock and monocalcium phosphate as P-sources when grown in soil. Journal of the Science of Food and Agriculture 60:205-211.

Hedley, M.J., and N.S. Bolan. 1997. Developments in some aspects of reactive phosphate rock research and use in New Zealand. Australian Journal of Experimental Agriculture 37:861-884.

Hinsinger, P., and R.J. Gilkes. 1995. Root-induced dissolution of phosphate rock in the rhizosphere of lupins grown in alkaline soil. Australian Journal of Soil Research 33:477-489.

Hoffland, E., G.R. Findenegg, and J.A. Nelemans. 1989. Solubilization of rock phosphate by rape. II. Local root exudation of organic acids as a response to P-starvation. Plant and Soil 113:161-165.

Hoffman, E., and D. Mayer. 1953. Solubility of phosphoric acid and phosphate rocks. Zeitschrift für Pflanzeneranchrung, Duengung und Bodenkunde 62:262–4.

Hughes, J.C., and R.J. Gilkes. 1984. The effect of chemical extractant on the estimation of rock phosphate fertiliser dissolution. Australian Journal of Soil Research 22:475-481.

Hughes, J.C., and R.J. Gilkes. 1986. The effect of soil properties and level of fertilizer application on the dissolution of Sechura rock phosphate in some soils from Brazil, Colombia, Australia and Nigeria. Australian Journal of Soil Research 24:219-227.

Hughes, J.C., and R.J. Gilkes. 1994. Rock phosphate dissolution and bicarbonate-soluble-P in some soils from South-Western Australia. Australian Journal of Soil Research 32:767-779.

Jamieson, P.D. 1985. Irrigation response of potatoes. Agronomy Society of New Zealand, Special Publication No 3: 17-20.

Jamieson, P.D., R.F. Zyskowski, S.M. Sinton, H.E. Brown, and R.C. Butler. 2006. The Potato Calculator: a tool for scheduling nitrogen fertilizer applications. Agronomy New Zealand 36:49-53.

Jenkins, P.D., and S. Mahmood. 2003. Dry matter production and partitioning in potato plants subjected to combined deficiencies of nitrogen, phosphorus and potassium. Annals of Applied Biology 143.

Jones, W.W. 1966. Chapter 22. Nitrogen, p. 310-323, *In* H. D. Chapman, ed. Diagnostic criteria for plants & soils. University of California. Divison of Agricultural Sciences. Riverside, California.

Kanabo, I., and R.J. Gilkes. 1988a. A comparison of mixed and band applications on the dissolution of North Carolina phosphate rock and on bicarbonate-soluble soil phosphorus. Fertilizer Research 15:3-12.

Kanabo, I.A.K., and R.J. Gilkes. 1987a. The influence of the addition of goethite to soil on the dissolution of North Carolina phosphate rock. Australian Journal of Soil Research 25:313-322.

Kanabo, I.A.K., and R.J. Gilkes. 1987b. The role of soil pH in the dissolution of phosphate rock fertilizers. Fertilizer Research 12:165-173.

Kanabo, I.A.K., and R.J. Gilkes. 1987c. A comparison between plant response and chemical measurements of the dissolution of reactive phosphate rock in soils of different pH and phosphorus retention. Australian Journal of Soil Research 25:451-460.

Kanabo, I.A.K., and R.J. Gilkes. 1988b. The effects of moisture regime and incubation period on the dissolution of North Carolina phosphate rock in soil. Australian Journal of Soil Research 26:153-163.

Kanabo, I.A.K., and R.J. Gilkes. 1988c. The effect of the level of phosphate rock application on its dissolution in soil and on bicarbonate-soluble phosphorus. Fertilizer Research 16:67-85.

Khasawneh, F.E., and E.C. Doll. 1978. The use of phosphate rock for direct application to soils. Advances in Agronomy 30:159-206.

Kirk, G.J.D., and P.H. Nye. 1986a. A simple-model for predicting the rates of dissolution of sparingly soluble calcium phosphates in soil. 1. The basic model. Journal of Soil Science 37:529-540.

Kirk, G.J.D., and P.H. Nye. 1986b. A simple-model for predicting the rates of dissolution of sparingly soluble calcium phosphates in soil. 2. Applications of the model. Journal of Soil Science 37:541-554.

Kumar, V., R.J. Gilkes, and M.D.A. Bolland. 1992a. Phosphate fertilizer compounds in soils - their influence on the relationship between plant-yield and soil test value. Communications in Soil Science and Plant Analysis 23:1461-1477.

Kumar, V., R.J. Gilkes, and M.D.A. Bolland. 1992b. A comparison of 7 soil-P tests for plant-species with different external-P requirements grown on soils containing rock phosphate and superphosphate residues. Fertilizer Research 33:35-45.

Kumar, V., R.J. Gilkes, and M.D.A. Bolland. 1993a. The agronomic effectiveness of reactive rock phosphate, partially acidulated rock phosphate and monocalcium phosphate in soils of different pH. Fertilizer Research 34:161-171.

Kumar, V., R.J. Gilkes, and M.D.A. Bolland. 1993b. Forms of phosphate in soils fertilized with rock phosphate and superphosphate as measured by chemical fractionation. Australian Journal of Soil Research 31:465-480.

Larsen, S., and A.E. Widdowson. 1968. Chemical composition of soil solution. Journal of the Science of Food and Agriculture 19:693-695.

Lee, A., J.H. Watkinson, G. Orbell, J. Bagyaraj, and D.R. Lauren. 1987. Factors influencing dissolution of phosphate rock and oxidation of elemental sulphur in some New Zealand soils. New Zealand Journal of Agricultural Research 30:373-385.

Lewis, D.C., R.P. Hindell, and J. Hunter. 1997. Effects of phosphate rock products on soil pH. Australian Journal of Experimental Agriculture 37:1003-1008.

Li, X.L., E. George, and H. Marschner. 1991. Extension of the phosphorus depletion zone in va-mycorrhizal white clover in a calcareous soil. Plant and Soil 136:41-48.

Loganathan, P., M.J. Hedley, M.R. Bretherton, and J.S. Rowarth. 2004. Accounting for particle movement when assessing the dissolution of slow release fertilizers in field soils. Nutrient Cycling in Agroecosystems 70:77-84.

Mackay, A.D., and J.K. Syers. 1986. Effect of phosphate, calcium, and pH on the dissolution of a phosphate rock in soil. Fertilizer Research 10:175-184.

Mackay, A.D., J.K. Syers, R.W. Tillman, and P.E.H. Gregg. 1986. A simple-model to describe the dissolution of phosphate rock in soils. Soil Science Society of America Journal 50:291-296.

Madibbo, G.M. 1998. Sorghum response to phosphate rock as affected by placement, application rate and soil type. Sudan Journal of Agricultural Research 1:17-19.

Maloth, S., and R. Prasad. 1976. Relative efficiency of rock phosphate and superphosphate for cowpea (*Vigna sinensis* Savi) fodder. Plant and Soil 45:295-300.

Martin, R.J., P.D. Jamieson, D.R. Wilson, and G.S. Francis. 1992. Effects of soil moisture deficits on yield and quality of 'Russet Burbank' potatoes. New Zealand Journal of Crop and Horticultural Science 20:1-9.

Mathur, B.S., and S. Lal. 1989. Effect of graded levels of rockphosphate on plant nutrition on an Alfisol. Journal of the Indian Society of Soil Science 37:491-494.

Mba, C.C. 1994. Rock phosphate solubilizing and cellulolytic actinomycete isolates of earthworm casts. Environmental Management 18:257-261.

Mengel, K., E.A. Kirkby, H. Kosegarten, and T. Appel. 2001. Principles of plant nutrition. 5th ed. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Montenegro, A., and F. Zapata. 2002. Rape genotypic differences in P uptake and utilization from phosphate rocks in an Andisol of Chile. Nutrient Cycling in Agroecosystems 63:27-33.

Nagaraja, H.M., B.K. Ramachandrappa, and H.V. Nanj. 1997. Response of dual purpose linseed to irrigation schedules and phosphorus levels through Mussoorie rockphosphate with *Aspergillus awamori*. Indian Agriculturist 41:115-121.

Nguyen, M.L., R.J. Haynes, and K.M. Goh. 1995. Nutrient budgets and status in 3 pairs of conventional and alternative mixed cropping farms in Canterbury, New-Zealand. Agriculture Ecosystems & Environment 52:149-162.

Nying, C.S., and S.J. Robinson. 2006. Factors influencing the dissolution of phosphate rock in a range of high P-fixing soils from Cameroon. Communications in Soil Science and Plant Analysis 37:2627-2645.

Prasad, M., T.M. Spiers, and I.C. Ravenwood. 1988. Target phosphorus soil test values for vegetables. New Zealand Journal of Experimental Agriculture 16:83-90.

Prokopy, W.R. 1993. Determination of Phosphate in Olsen's Extracts of Soil by Flow Injection Analysis. Lachat Instruments Methods Manual. Revised 18 April, 2001.

Puha, M., S.R. Shaw, and H.J. Kerckhoffs. 2005. The East Coast Organic Producers Trust; Current production and production limitations. Crop and Food Research Ltd, Hastings.

Rajan, S.S.S. 1983. Effect of sulphur content of phosphate rock/sulphur granules on the availability of phosphate to plants. Fertilizer Research 4:287-296.

Rajan, S.S.S., M.W. Brown, M.K. Boyes, and M.P. Upsdell. 1992. Extractable phosphorus to predict agronomic effectiveness of ground and unground phosphate rocks. Fertilizer Research 32:291-302.

Rajan, S.S.S., and E.A. Edge. 1980. Dissolution of granulated low-grade phosphate rocks, phosphate rocks/sulphur (biosuper), and superphosphate in soil. New Zealand Journal of Agricultural Research 23:451-456.

Rajan, S.S.S., R.L. Fox, and W.M.H. Saunders. 1991a. Influence of pH, time and rate of application on phosphate rock dissolution and availability to pastures. 2. Soil chemical studies. Fertilizer Research 28:95-101.

Rajan, S.S.S., R.L. Fox, W.M.H. Saunders, and M. Upsdell. 1991b. Influence of pH, time and rate of application on phosphate rock dissolution and availability to pastures. 1. Agronomic benefits. Fertilizer Research 28:85-93.

Reddy, M.S., S. Kumar, and K. Babita. 2002. Biosolubilization of poorly soluble rock phosphates by *Aspergillus tubingensis* and *Aspergillus niger*. Bioresource Technology 84:187-189.

Reid, J.B. 2002. Yield response to nutrient supply across a wide range of conditions. 1. Model derivation. Field Crops Research 77.

Reid, R.B., and S.R. Shaw. 2008. Potential for maize to recycle leached soil nitrogen. Proceedings of the 21st Annual Workshop held by the Fertiliser and Lime Research Centre Massey University:446-478.

Rijkse, W.C. 1980. Soils and Agriculture of Waiapu valley, East Coast, North Island, New Zealand. New Zealand Soil Survey Report 60:86.

Robinson, J.S., and J.K. Syers. 1991. Effects of solution calcium-concentration and calcium sink size on the dissolution of Gafsa phosphate rock in soils. Journal of Soil Science 42:389-397.

Robinson, J.S., J.K. Syers, and N.S. Bolan. 1994. A simple conceptual-model for predicting the dissolution of phosphate rock in soils. Journal of the Science of Food and Agriculture 64:397-403.

Rodriguez, H., and R. Fraga. 1999. Phosphate solubilizing bacteria and their role in plant growth promotion. Biotechnology Advances 17:319-339.

Romer, W., and P. Lehne. 2004. Neglected P and K fertilization in organic farming reduces N-2 fixation and grain yield in a red clover-oat rotation. Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde 167:106-113.

Russell, E.W. 1988. Russell's soil conditions and plant growth. 11th ed. Longman Scientific and Technical, New York.

Saggar, S., M.J. Hedley, R.E. White, P.E.H. Gregg, K.W. Perrott, and I.S. Cornforth. 1992. Development and evaluation of an improved soil test for phosphorus 2. Comparison of the Olsen and mixed cation-anion exchange resin tests for predicting the yield of ryegrass grown in pots. Fertilizer Research 33:135-144.

Saggar, S., M.J. Hedley, R.E. White, K.W. Perrott, P.E.H. Gregg, I.S. Cornforth, and A.G. Sinclair. 1999. Development and evaluation of an improved soil test for phosphorus 3. field comparison of Olsen, Colwell and resin soil P tests for New Zealand pasture soils. Nutrient Cycling in Agroecosystems 55:35-50.

Sale, P.W.G., P.G. Simpson, D.C. Lewis, R.J. Gilkes, M.D.A. Bolland, D.A. Ratkowsky, M.A. Gilbert, D.L. Garden, J.W.D. Cayley, and D. Johnson. 1997. The agronomic effectiveness of reactive phosphate rocks 1. Effect of the pasture environment. Australian Journal of Experimental Agriculture 37:921-936.

Sands, P.J., C. Hackett, and H.A. Nix. 1979. A model of the development and bulking of potatoes (*Solanum tuberosum* L.). 1. Derivation from well-managed field crops. Field Crops Research 2:309-331.

Scholefield, D., R.D. Sheldrick, T.M. Martyn, and R.H. Lavender. 1999. A comparison of triple superphosphate and Gafsa ground rock phosphate fertilisers as P-sources for grass-clover swards on a poorly-drained acid clay soil. Nutrient Cycling in Agroecosystems 53:147-155.

Seshadri, S., S. Ignacimuthu, and C. Lakshminarasimhan. 2004. Effect of nitrogen and carbon sources on the inorganic phosphate solubilization by different *Aspergillus niger* strains. Chemical Engineering Communications 191:1043-1052.

Shin, W., J. Ryu, S. Choi, C. Kim, R. Gadagi, M. Madhaiyan, S. Seshadri, J. Chung, and T. Sa. 2005. Solubilization of hardly soluble phosphates and growth promotion of maize (*Zea mays* L.) by *Penicillium oxalicum* isolated from rhizosphere. Journal of Microbiology and Biotechnology 15:1273-1279.

Simpson, P.G., P.W.G. Sale, and S.B. Tennakoon. 1997a. An economic analysis of the field performance of North Carolina reactive phosphate rock compared with single superphosphate for selected sites from the National Reactive Phosphate Rock Project. Australian Journal of Experimental Agriculture 37:1061-1076.

Simpson, P.G., A.J. Weatherley, P.W.G. Sale, M.J. McLaughlin, V. Hoy, and P. Lancaster. 1997b. Assessment of soil phosphorus tests for situations in Australia where reactive phosphate rock and water-soluble phosphorus fertilisers are used. Australian Journal of Experimental Agriculture 37:1027-1035.

Sinclair, A.G., P.D. Johnstone, L.C. Smith, M.B. O'Connor, and L. Nguyen. 1993. Agronomy, modelling and economics of reactive phosphate rocks as slow-release phosphate fertilizers for grasslands. Fertilizer Research 36.

Sinclair, A.G., P.D. Johnstone, J.H. Watkinson, L.C. Smith, J. Morton, and A. Judge. 1998. Comparison of six phosphate rocks and single superphosphate as phosphate fertilisers for clover-based pasture. New Zealand Journal of Agricultural Research 41:415-420.

Sinclair, C. 2002. BioPhos [Online] http://www.gardenews.co.nz/BioPhos%20Booklet.pdf (verified 2-May-2008).

Singh, H.P., and T.A. Singh. 1993. The interaction of rockphosphate, *Bradyrhizobium*, vesicular-arbuscular mycorrhizae and phosphate-solubilizing microbes on soybean grown in a sub-Himalayan mollisol. Mycorrhiza 4:37.

Singh, S., and K.K. Kapoor. 1998. Effects of inoculation of phosphate-solubilizing microorganisms and an arbuscular mycorrhizal fungus on mungbean grown under natural soil conditions. Mycorrhiza 7:249.

Singh, S., and K.K. Kapoor. 1999. Inoculation with phosphate-solubilizing microorganisms and a vesicular arbuscular mycorrhizal fungus improves dry matter yield and nutrient uptake by wheat grown in a sandy soil. Biology and Fertility of Soils 28:139-144.

Smalberger, S.A., U. Singh, S.H. Chien, J. Henao, and P.W. Wilkens. 2006. Development and validation of a phosphate rock decision support system. Agronomy Journal 98:471-483.

Smyth, A.J., and J. Dumanski. 1995. A framework for evaluating sustainable land management. Canadian Journal of Soil Science 75:401-406.

Stamford, N.P., P.R. Santos, C.E.S. Santos, A.D.S. Freitas, S.H.L. Dias, and M.A. Lira. 2007. Agronomic effectiveness of biofertilizers with phosphate rock, sulphur and *Acidithiobacillus* for yam bean grown on a Brazilian tableland acidic soil. Bioresource Technology 98:1311-1318.

Stephen, R.C., and O.T. Roberts. 1983. Pot experiments 1. Evaluation of directly-applied phosphate rocks and phosphate rock/sulphur assemblages New Zealand Fertilisers Manufacturers Research Association Incorporated, Annual Report 1982-83. Otara Research Station, Auckland New Zealand.

Stone, P., I. Sorensen, and B. Rogers. 1999. A simple model of potato growth and yield. Agronomy New Zealand 29:59-61.

Syres, J.K., A.D. MacKay, and P.E.H. Gregg. 1981. Chemical reactivity of phosphate rock materials. Proceedings of the Technical Workshop on - Potential of phosphate rock as a direct application fertilizer in New Zealand. Massey University 3:74-81.

Tate, K.R., T.W. Speir, D.J. Ross, K.N. Parfitt, K.N. Whale, and J.C. Cowling. 1991. Temporal variations in some plant and soil P pools in two pasture soils of widely different P fertility status. Plant and Soil 132:219-232.

Vassilev, N., I. Franco, M. Vassileva, and R. Azcon. 1996. Improved plant growth with rock phosphate solubilized by *Aspergillus niger* grown on sugarbeet waste. Bioresource Technology 55:237-241.

Vassilev, N., A. Medina, R. Azcon, and M. Vassileva. 2006. Microbial solubilization of rock phosphate on media containing agro-industrial wastes and effect of the resulting products on plant growth and P uptake. Plant and Soil 287:77-84.

Vora, M.S., and H.N. Shelat. 1998. Impact of addition of different carbon and nitrogen sources on solubilization of rock phosphate by phosphate-solubilizing micro-organisms. Indian Journal of Agricultural Sciences 68:292-294.

Wang, G.H., D.R. Zhou, Q. Yang, J. Jin, and X.B. Liu. 2005. Solubilization of rock phosphate in liquid culture by fungal isolates from rhizosphere soil. Pedosphere 15:532-538.

Watkinson, J.H. 1994a. Modelling the dissolution rate of reactive phosphate rock in New Zealand pastoral soils. Australian Journal of Soil Research 32:739-753.

Watkinson, J.H. 1994b. Dissolution rate of phosphate rock particles having a wide-range of sizes. Australian Journal of Soil Research 32:1009-1014.

Watson, C.A., D. Atkinson, P. Gosling, L.R. Jackson, and F.W. Rayns. 2002. Managing soil fertility in organic farming systems. Soil Use and Management 18:239-247.

Whitelaw, M.A. 2000. Growth promotion of plants inoculated with phosphate-solubilizing fungi. Advances in Agronomy 69:99-151.

Wild, A., and L.H.P. Jones. 1988. Mineral nutrition of crop plants, p. 69-112, *In* A. Wild, ed. Russell's Soil Conditions and Plant Growth, 11th ed. Longman Scientific and Technical, Reading, UK.

Wright, R.J., V.C. Baligar, and D.P. Belesky. 1992. Dissolution of North-Carolina phosphate rock in soils of the Appalachian region. Soil Science 153:25-36.

Wright, R.J., V.C. Baligar, D.P. Belesky, and J.D. Snuffer. 1991. The effect of phosphate rock dissolution on soil chemical-properties and wheat seedling root elongation. Plant and Soil 134:21-30.

Zhu, Y.G., Y.Q. He, S.E. Smith, and F.A. Smith. 2002. Buckwheat (*Fagopyrum esculentum* Moench) has high capacity to take up phosphorus (P) from a calcium (Ca)-bound source. Plant and Soil 239:1-8.