Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.
FIELD AND LABORATORY STUDIES
OF THE MOVEMENT AND REACTIONS
OF PHOSPHORUS IN SOILS

A thesis presented in partial fulfilment of
the requirements for the degree of
Doctor of Philosophy in Soil Science
at Massey University

Alexander Marinus Dick Reunes
1978
ABSTRACT

Low and stable concentrations of phosphorus (P) forms and sediment were obtained in stream flow from two small, adjacent, scrub-covered, and minimally-disturbed catchments near Palmerston North, New Zealand. In contrast, higher and irregular concentrations and loadings were obtained following land clearing, P fertilizer application, and the establishment of grazed pasture. The need for intensive stream sampling, as well as complete hydrograph data in order to obtain reliable information on stream loadings, is emphasised.

High and fluctuating concentrations of P forms and sediment were obtained following the change in land use. A high proportion of the P and sediment loss occurred in the storm runoff component of stream flow. The estimated losses of fertilizer P in stream flow (approximately 1% of that added) were very small from an agronomic standpoint but they represent large proportional increases in the loadings of P forms in stream flow.

The high amounts of water-extractable P present in the soils of the catchment (field soils), immediately following the aerial application of fertilizer P, declined rapidly to lower, more stable values. This pattern of decline for field soils was replicated using small pots established in the field (pot soils) and containing fertilized soil representative of the catchments. Close correlations were obtained between water-extractable P in the upper 1cm of field and pot soils, and mean dissolved inorganic P (DIP) concentrations in the surface runoff component of stream flow in closely-following storms. The possibility of predicting DIP losses in
surface runoff from soils using a water-extraction technique is thus indicated.

The decrease with time in the amounts of water-extractable P observed after superphosphate addition to field and pot soils was reproduced in the laboratory. This relationship validated the use of laboratory studies to examine the rate and extent of interaction of fertilizer P occurring in field soils and to predict the potential movement of fertilizer P from soils to waters.

The decline in water-extractable P closely paralleled the decrease in plant uptake of P with time following fertilizer P addition to two contrasting soils. This suggested that water extraction may be a useful soil-testing procedure for predicting P availability to plants, as well as the movement of P in surface runoff from soils.

The rate of decline in water-extractable P in a given soil was proportional to both the amount of P added and the amount initially extractable immediately following P addition. This suggests that the rate and extent of P sorption in a soil is directly related to soil solution P concentration. Differences were obtained, however, between three contrasting soils in the relative rate and extent of P sorption.

A kinetic model based on the Langmuir equation was developed to simulate the decline in water-extractability of P added to three soils. Three populations of sites were assumed and the appropriate sorption maxima and binding energy constants were derived from sorption isotherm studies. The model provided a satisfactory prediction of the fate of different amounts of fertilizer P. It is probable that the further development of this model would provide a useful basis for predicting the fate of P added to soils and the potential movement of added P in surface-runoff waters.
ACKNOWLEDGEMENTS

I would like to express my gratitude to a number of people without whose help and support this thesis would never have eventuated. In particular I would like to thank:

My supervisor, Professor Keith Syers, to whom I am deeply indebted for his buoyant enthusiasm, encouragement, and friendship. Further to this, his rigorous standards of scientific thoroughness and presentation, while sometimes trying, have been highly rewarding.

Mr. Russell Tillman, to whom I am particularly grateful for his friendship, patience, and continual assistance during the planning, execution and presentation of this study.

Other members of the Department of Soil Science staff, both teaching and technical, and my colleagues who provided assistance and good humour.

Julie, for her patience over the long duration of the study and her forebearance of difficulties.

Dianne, for producing first-class typescript.

The University Grants Committee for a postgraduate scholarship for three years.

The Faculty of Agricultural and Horticultural Science, Massey University, for a Massey postgraduate scholarship.

The Waikato Valley Authority for time and encouragement to complete this thesis.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xvi</td>
</tr>
</tbody>
</table>

## CHAPTER 1

**REVIEW OF LITERATURE**

1.1 Importance of Phosphorus Forms and Concentrations in Surface Waters ........................................ 1

1.2 Factors Influencing Phosphorus Enrichment of Surface Waters .................................................. 4

1.2.1 Natural or background phosphorus concentrations ............................................................ 4

1.2.2 Urban land use ....................................................................................................................... 7

1.2.3 Rural land use ....................................................................................................................... 8

1.2.3.1 Forestry .......................................................................................................................... 8

1.2.3.2 Livestock farming ........................................................................................................ 10

1.2.3.3 Cropping ......................................................................................................................... 11

1.2.3.4 Fertilizer ......................................................................................................................... 13

1.2.4 Relative importance of factors influencing the phosphorus enrichment of waters .................. 16

1.3 Movement of Phosphorus from Soils to Surface Waters .................................................................. 17

1.3.1 Sources of water and phosphorus .......................................................................................... 17

1.3.1.1 Surface runoff .............................................................................................................. 19

1.3.1.2 Subsurface runoff .......................................................................................................... 20

1.3.2 Potential influence of changes in land use on phosphorus movement to water .................. 21

1.4 Forms and Reactions of Phosphorus in Soils ................................................................................. 23

1.4.1 Organic phosphorus in soils .................................................................................................. 23
1.4.2 Inorganic phosphorus in soils
1.4.2.1 Primary inorganic phosphorus
1.4.2.2 Secondary inorganic phosphorus

1.5 Modelling the Reactions and Reaction Rates of Phosphorus

### 1.5.1 Reactions
- 1.5.1.1 Isotherm resolution of data
- 1.5.1.2 Reaction mechanisms

### 1.5.2 Reaction rates

### 1.5.3 Prediction of phosphorus movement from soils and catchments to water

1.6 General Conclusions and Research Needs

---

### CHAPTER 2

**GENERAL MATERIALS AND METHODOLOGY**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Description of the Catchments</td>
<td>47</td>
</tr>
<tr>
<td>2.2 Monitoring Equipment</td>
<td>52</td>
</tr>
<tr>
<td>2.3 Sample Collection</td>
<td>56</td>
</tr>
<tr>
<td>2.3.1 Water samples</td>
<td>56</td>
</tr>
<tr>
<td>2.3.2 Soil samples</td>
<td>56</td>
</tr>
<tr>
<td>2.4 Analytical Procedures</td>
<td>57</td>
</tr>
<tr>
<td>2.5 Data Processing</td>
<td>57</td>
</tr>
</tbody>
</table>

### CHAPTER 3

**MOVEMENT OF WATER, SEDIMENT, AND PHOSPHORUS FORMS FROM TWO SMALL, ADJACENT CATCHMENTS UNDER CHANGING LAND USE**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Introduction</td>
<td>59</td>
</tr>
<tr>
<td>3.2 Materials and Methods</td>
<td>61</td>
</tr>
</tbody>
</table>
### 3.3 Results and Discussion

- **3.3.1 Flow-concentration relationships**
- **3.3.2 Sources of water, sediment, and phosphorus forms**
- **3.3.3 Impact of land clearing and changing land use on sediment and phosphorus movement**
  - **3.3.3.1 Movement of sediment and particulate phosphorus**
  - **3.3.3.2 Movement of dissolved inorganic and organic phosphorus**
- **3.3.4 Influence of phosphorus fertilizer on the movement of phosphorus forms from the catchments**

### 3.4 General Discussion

---

### CHAPTER 4

**FATE OF APPLIED PHOSPHORUS ADDED TO SOILS AND MOVEMENT IN RUNOFF WATER**

- **4.1 Introduction**
- **4.2 Materials and Methods**
  - **4.2.1 Preliminary investigation**
  - **4.2.2 Detailed investigation**
  - **4.2.3 Supplementary study**
- **4.3 Results and Discussion**
  - **4.3.1 Changes in water-extractable phosphorus in soil from fertilized and control field sites within the catchments**
  - **4.3.2 Changes in water-extractable phosphorus in soil from fertilized and control pots in the field**
    - **4.3.2.1 Treatment differences and phosphorus movement from the upper lcm**
    - **4.3.2.2 Relationships between water-extractable phosphorus data obtained for soils from fertilized field sites and pots**
    - **4.3.2.3 Regeneration of the water-extractable phosphorus pool in soils**
4.3.3 Relationships between mean dissolved inorganic phosphorus concentrations in surface runoff and water-extractable phosphorus values obtained for soils from fertilized field sites and pots ........................................ 143

4.4 General Discussion ........................................ 150

CHAPTER 5

THE RATE AND EXTENT OF PHOSPHORUS REACTIONS IN SOILS ........................................ 159

5.1 Introduction ........................................ 159

5.2 Materials and Methods ................................. 161

5.2.1 Comparison of extraction techniques to estimate labile phosphorus in soils .......... 161

5.2.2 Soils used in subsequent laboratory studies ... 161

5.2.3 Preliminary laboratory studies of the decline in water-extractable phosphorus following phosphorus addition to one soil .......... 162

5.2.4 Laboratory and glasshouse studies of the decline in water-extractable and plantavailable phosphorus in contrasting soils following phosphorus addition .......... 164

5.2.5 Comparisons between solid and liquid additions of phosphorus to soils ............. 165

5.2.6 Detailed studies of the decline in water-extractable phosphorus in soils .......... 166

5.3 Results and Discussion ................................. 171

5.3.1 Comparison of extraction techniques ............ 171

5.3.2 Decline in water-extractable phosphorus following phosphorus addition to one soil .......... 171
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3.3</td>
<td>Decline in water-extractable and plant-available phosphorus in contrasting soils following phosphorus addition</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>5.3.3.1 Characteristics of the decline in water-extractable phosphorus in soils of contrasting phosphorus sorption properties</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>5.3.3.2 Decline in water-extractability of phosphorus in soil and the availability of phosphorus to plants</td>
<td>179</td>
</tr>
<tr>
<td>5.3.4</td>
<td>Influence of solid or dissolved phosphorus addition to soil on the decline in water-extractable phosphorus</td>
<td>188</td>
</tr>
<tr>
<td>5.3.5</td>
<td>Detailed studies of the decline in water-extractable phosphorus in soils and an approach to modelling soil phosphorus reactions</td>
<td>192</td>
</tr>
<tr>
<td>5.4</td>
<td>General Discussion</td>
<td>207</td>
</tr>
<tr>
<td></td>
<td>SUMMARY AND CONCLUSIONS</td>
<td>216</td>
</tr>
<tr>
<td></td>
<td>BIBLIOGRAPHY</td>
<td>219</td>
</tr>
<tr>
<td></td>
<td>APPENDICES</td>
<td>238</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>2.1</td>
<td>Map of the North Island of New Zealand showing the general location of the study area in the inset</td>
<td>48</td>
</tr>
<tr>
<td>2.2</td>
<td>Map of the study area (from inset on Fig. 2.1) showing location of catchments (circle), local drainage networks, and indicating topography</td>
<td>49</td>
</tr>
<tr>
<td>2.3</td>
<td>Vertical aerial photography of the two catchments before (A) and after (B) clearing</td>
<td>51</td>
</tr>
<tr>
<td>2.4</td>
<td>Vertical aerial photograph of the two catchments showing cleared slopes and debris deposition following clearing</td>
<td>53</td>
</tr>
<tr>
<td>2.5</td>
<td>Ground photograph in the 22-ha catchment after clearing showing soil surface disturbances, steepness of slopes, and debris in stream channel</td>
<td>54</td>
</tr>
<tr>
<td>2.6</td>
<td>H-S flume and Stevens F-type flow recorder operating on the stream draining the 6-ha catchment</td>
<td>55</td>
</tr>
<tr>
<td>3.1</td>
<td>Components of a stream hydrograph</td>
<td>63</td>
</tr>
<tr>
<td>3.2</td>
<td>Variation in flow and concentrations of PP and sediment in storm discharge from the 22-ha catchment during the storm event of 24-25/6/1974 before land clearing</td>
<td>65</td>
</tr>
<tr>
<td>3.3</td>
<td>Variation in flow and concentrations of PP and sediment in storm discharge from the 22-ha catchment during the storm event of 26/5/1975 after land clearing</td>
<td>66</td>
</tr>
<tr>
<td>3.4</td>
<td>Variation in mean concentrations of sediment and PP in the storm discharge of successive storm events throughout 1974, 1975 and 1976 for the 22-ha catchment</td>
<td>67</td>
</tr>
<tr>
<td>3.5</td>
<td>Variations in mean concentrations of sediment and PP in storm discharge of successive storm events throughout 1974 and 1975 for the 6-ha catchment</td>
<td>68</td>
</tr>
</tbody>
</table>
FIGURE 3.6 Variation in flow and concentrations of DIP and DOP in storm discharge from the 22-ha catchment during the storm event of 24-25/6/1974 before land clearing ............................................ 69

3.7 Variation in flow and concentrations of DIP and DOP in storm discharge from the 22-ha catchment during the storm event of 26/5/1975 after land clearing ............................................ 71

3.8 Variation in mean concentrations of DIP and DOP in the storm discharge of successive storm events throughout 1974, 1975, and 1976 for the 22-ha catchment ............................................ 87

3.9 Variation in mean concentrations of DIP and DOP in the storm discharge of successive storm events throughout 1974 and 1975 for the 6-ha catchment ............................................ 88

3.10 Influence of fertilizer P application on the variation in mean concentrations of DIP (A) and PP (B) in the storm discharge of successive storm events from two adjacent catchments, both of which were fertilized in 1975 but only one of which was fertilized in 1976 ............................................ 97

3.11 Regression between mean concentrations of DIP in storm flow from the 22-ha and 6-ha catchments in 1975 (both catchments fertilized) and in 1976 (6-ha catchment only fertilized) ............................................ 99

3.12 Regression between mean PP and sediment concentrations in storm flow from the 6-ha catchment (A) and the 22-ha catchment (B) in 1976 following fertilizer addition to the 6-ha catchment only ............................................ 105

4.1 Plan of the two catchments showing the location of 6 sites for soil sampling in 1975 (A, B, C, D, E, and F) and the three transect lines for placement of pots to estimate the mean superphosphate application rates in the catchments ............................................ 115

4.2 Transverse section of the three transect lines shown in Fig. 4.1 showing the location of pots placed in the catchments to estimate the application rate of superphosphate ............................................ 116
4.3 Decline in water-extractable P in soils with time following fertilizer P addition at three fertilized sites and from three control sites in 1975 .......... 124

4.4 Decline in water-extractable P in soils with time following fertilizer P addition at three fertilized sites and from three control sites in the 6-ha catchment only in 1976 .......... 126

4.5 Decline in water-extractable P in soils with time following fertilizer P addition at three fertilized sites in the 6-ha catchment only in 1976 and three fertilized sites in both catchments in 1975 .......... 127

4.6 Relative water-extractability of P, expressed as a proportion of the initial extraction value, with time following fertilizer P addition at three fertilized sites in the 6-ha catchment only in 1976 and three fertilized sites in both catchments in 1975 .......... 129

4.7 Decline in water-extractable P with time, following fertilizer P addition, in soil from field pots .......... 131

4.8 Relative water-extractability of P, expressed as a proportion of the initial extraction value, with time following fertilizer P addition to soil in field pots .......... 133

4.9 Field pots involving "divided" soil treatments showing condition at time of fertilizer placement and after 40 days in the field .......... 135

4.10 Decline in water-extractable P with time, following fertilizer P addition, in soil from fertilized sites in the field and pots in the field .......... 137

4.11 Regression between water-extractable P in soil from fertilized field sites (B) and from surface 2-cm pot treatment (A). All data for the 6-ha catchment in 1976 .......... 138
Regression between water-extractable P in soil from fertilized field sites (B) and from mixed pot treatment (A). All data for the 6-ha catchment in 1976.

Regression between DIP concentrations in the leachates from 20 pots (mixed treatment after 7 months in the field) obtained by successive leachings.

Relationship between mean DIP concentrations in the surface runoff component of storm flow from the two catchments and water-extractable P in soil from fertilized field sites in 1975.

Regression between mean DIP concentrations in the surface runoff component of selected storm flow and water-extractable P in soil from fertilized field sites in 1975.

Relationship between mean DIP concentrations in the surface runoff components of storm flow from the 6-ha catchment and water-extractable P in soil from fertilized field sites in the 6-ha catchment in 1976.

Regression between mean DIP concentrations in the surface runoff component of storm flow from the 6-ha catchment and water-extractable P in soil from fertilized field sites in the 6-ha catchment in 1976, combining 1975 and 1976 data.

Regression between mean DIP concentrations in the surface runoff component of storm flow from the 6-ha catchment in 1976 and water-extractable P in soil from surface 2-cm pot treatments.

Regression between mean DIP concentrations in the surface runoff component of storm flow from the 6-ha catchment in 1976 and water-extractable P in soil from the mixed pot treatments.
| FIGURE 5.1 | Regression between water-extractable P values obtained in two sequential water extractions (each of 1 hour duration at a soil:solution ratio of 1:40) (B) and in one water extraction (17 hours duration and at a soil:solution ratio of 1:400) (A) ............................................. 172 |
| 5.2 | Decline in water-extractable P (two 1-hour extractions at a soil:solution ratio of 1:40) with time from soil incubated in pots following fertilizer P addition ............................................. 173 |
| 5.3 | Relative water extractability of P, expressed as a proportion of the initial extraction value, with time following P addition at three rates ............................................. 174 |
| 5.4 | Decline in water-extractable P in catchment field soils and in incubation pots of the same soil following fertilizer P addition ............................................. 177 |
| 5.5 | Decline in water-extractable P from Pahiatua and Egmont soils with time following incubation and fertilizer P addition ............................................. 178 |
| 5.6 | Decline in water-extractable P from Pahiatua soil with time following incubation and fertilizer P addition ............................................. 180 |
| 5.7 | Decline in water-extractable P with time following fertilizer P addition and incubation of Egmont soil ............................................. 181 |
| 5.8 | Decline in recovery of P from Pahiatua soil with time following superphosphate addition and incubation ............................................. 183 |
| 5.9 | Regression between plant uptake of P from Pahiatua soil following superphosphate addition and incubation, and amounts of extractable P ............................................. 184 |
| 5.10 | Decline in recovery of P from Egmont soil with time following superphosphate addition and incubation ............................................. 185 |
| 5.11 | Regression between plant uptake of P from Egmont soil samples following superphosphate addition and incubation, and amounts of extractable P ............................................. 186 |
5.12 Regression between plant uptake of P from Pahiatua and Egmont soils following superphosphate addition and incubation, and extractable P ............... 187

5.13 Decline in recovery of P from Pahiatua soil with time following rock phosphate addition and incubation ............... 189

5.14 Decline in recovery of P from Egmont soil with time following rock phosphate addition and incubation ............... 190

5.15 Decline in water-extractable P from Pahiatua soil with time following fertilizer P addition at 75 μg P g⁻¹ in solid and liquid forms ............... 193

5.16 Decline in water-extractable P from Pahiatua soil following fertilizer P addition and incubation ............... 194

5.17 Decline in water-extractable P with time from Pahiatua soil following fertilizer P addition and incubation at three rates of addition ............... 195

5.18 Decline in water-extractable P with time from Dannevirke soil following fertilizer P addition and incubation at two rates of addition ............... 196

5.19 Decline in water-extractable P with time from Egmont soil following fertilizer P addition and incubation ............... 197

5.20 Decline in relative water extractability of P, expressed as a proportion of the extraction value obtained after 40 hours, with time following fertilizer P addition and incubation ............... 199

5.21 Schematic representation of the proposed reaction mechanisms involved in P sorption and desorption ............... 205

5.22 Predicted (---) and measured (——) decline in the amounts of water-extractable P in Pahiatua (a), Dannevirke (b), and Egmont (c) soils with time after fertilizer P addition ............... 206
FIGURE 5.23 Predicted (---) and measured (——) decline in the amounts of water-extractable P in Pahiatua soil with time after fertilizer P addition at rates of 150 $\mu$g P g$^{-1}$ (a) and 75 $\mu$g P g$^{-1}$ (b) ....... 208

5.24 Predicted (---) and measured (——) decline in the amounts of water-extractable P in Dannevirke soil with time after fertilizer P addition at rates of 150 $\mu$g P g$^{-1}$ (a) and 75 $\mu$g P g$^{-1}$ (b) ....... 209

5.25 Predicted (---) and actual (——) decline in the amounts of water-extractable P in Egmont soil with time after fertilizer P addition at rates of 150 $\mu$g P g$^{-1}$ (a) and 75 $\mu$g P g$^{-1}$ (b) ....... 210
TABLE 3.1 Flow from the 22-ha and 6-ha catchments for the years 1974, 1975, and 1976, showing total annual outputs of four forms of flow .......................... 72

3.2 Discharge of water, sediment, particulate P (PP), and total P (TP), from the two catchments in annual stream flow before land clearing (1974) and following clearing and fertilizer application (1975 and 1976) .. 77

3.3 Discharge of water, sediment, particulate P (PP) and total P (TP) from the two catchments in annual stream flow within storm events before land clearing (1974) and following clearing and fertilizer application (1975 and 1976) ............. 80

3.4 Discharge of water, sediment, particulate P (PP) and total P (TP) from the two catchments in annual storm flow before land clearing (1974) and following clearing and fertilizer application (1975 and 1976) .. 82

3.5 Discharge of water, sediment, particulate P (PP), and total P (TP) from the two catchments in annual subsurface flow before land clearing (1974), and following clearing and fertilizer application (1975 and 1976) ................. 84

3.6 Discharge of water, dissolved inorganic P (DIP), dissolved organic P (DOP), and total P (TP) from the two catchments in annual stream flow before land clearing (1974) and following clearing and fertilizer application (1975 and 1976) ............... 90

3.7 Discharge of water, dissolved inorganic P (DIP), dissolved organic P (DOP), and total P (TP) from the two catchments in annual stream flow within storm events before land clearing (1974) and following clearing and fertilizer application (1975 and 1976) .. 92

3.8 Discharge of water, dissolved inorganic P (DIP), dissolved organic P (DOP), and total P (TP) from the two catchments in annual storm flow before land clearing (1974) and following clearing and fertilizer application (1975 and 1976) ............... 94

3.9 Discharge of water, dissolved inorganic P (DIP), dissolved organic P (DOP), and total P (TP) from the two catchments in annual subsurface flow before land clearing (1974) and following clearing and fertilizer application (1975 and 1976) ............... 96
TABLE 3.10  Mean concentrations of particulate P (PP) and sediment, and amounts of PP associated with sediment in annual storm flow from the 22-ha and 6-ha catchments in 1974 (before clearing) and in 1975 and 1976 (following clearing and fertilizer application) .................. 102

3.11 Losses of P forms and sediment from fertilized (6-ha) and unfertilized (22-ha) catchments in 1976 showing losses per hectare, proportions of P forms lost, and mean concentrations in annual storm discharge ...................... 103

4.1 Application rate of fertilizer P at the soil surface obtained from sampling containers surrounding six potential soil-sampling sites in the preliminary investigation of 1975 .................. 121

4.2 Amounts of water-extractable P in soils from sites A, C and F (Fig. 4.1) and control sites on 24/3/1975 (before fertilizer application) and at various times after fertilizer was applied on 5/4/1975 ...................... 123

4.3 Regression analyses between amounts of water-extractable P in soils and mean DIP concentrations in the surface runoff component of stream flow for the two catchments during the two years of study .................. 151

5.1 Background data for three soils used in laboratory studies .................. 163

5.2 Correlation coefficients between plant uptake of P after 50 days growth in Pahiatua and Egmont soils fertilized with superphosphate and rock phosphate, and amounts of water-extractable P and Olsen-extractable P .................. 191

5.3 Amounts of total "native" P, determined using 32P, and the amounts of P present in each region, calculated from solution P concentrations at equilibrium with no P addition and the Langmuir equation for each region .................. 200

5.4 Sorption constants describing the three (I, II, and III) regions of P sorption for three soils; K and b are the equilibrium constant of reaction and the sorption maximum, respectively, for a particular region .................. 201