

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.

PHOSPHORUS CYCLING
IN
GRAZED, STEEP HILL COUNTRY

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

Allan Gilbert Gillingham

1978

ABSTRACT

Measurements of P uptake by pasture and P return in pasture litter and dung were made on two intensively grazed, north- and south-facing paddocks in steep hill country with soils of moderate to high P status. Both P uptake and more particularly the return of P in dung by grazing sheep, was high on the relatively level campsite areas but decreased sharply as ground surface slope increased. A high grazing pressure ensured that P return via litter was low relative to plant uptake.

A net P balance derived for differing paddock strata showed a large net annual gain of P on campsites (50.1 and 119.8 kg ha⁻¹ on north and south aspects, respectively) but a considerable net P loss from both 25° slopes (19.5 and 10.0 kg ha⁻¹ on north and south aspects, respectively) and 45° slopes (15.3 and 13.8 kg ha⁻¹ on north and south aspects, respectively). Differences between aspects in the net P balance could be explained by the overall difference in the topography of the two paddocks as it affected relative camping and grazing pressure on each stratum.

Subsequent simulation studies were conducted using a mathematical model based on field data from the north-aspect paddock and validated against results from the south-aspect paddock. Results obtained from the model indicated that the quantity of P transfer from slopes increased at a greater than directly proportionate rate as stocking rate increased and was also directly related to pasture P content.

Determination of relative root activity using ³²P showed that approximately 90% of P uptake by pasture in spring occurred from within 7cm of the soil surface. The greater proportion of this occurred within the 0-3cm soil depth. No significant P uptake occurred from depths greater than 30cm. Although the extent of P uptake from 0-3cm depth soil was

similar both upslope and downslope from a P source, the direction of predominant root activity at greater depths was affected by the steepness of slope, tending to be at an angle between vertical and that normal to the soil surface.

A technique was developed to characterize short term plant-available P, using both ^{32}P and ^{33}P . Results indicated that the $^{32}\text{P}/^{33}\text{P}$ ratio of the water-extractable P fraction more closely resembled that in the plant than was the case for the Olsen P extract. Both ryegrass (Lolium perenne) and white clover (Trifolium repens) apparently utilized P from the same soil pool, the measured higher P content of ryegrass in this study being due only to a more extensive and rapidly developing root system than that of clover.

The addition to soil of P extracted by water from litter, dung, and superphosphate sources showed that all forms had similar effects in increasing the water-extractable and Olsen P levels in the soil. Thus it could be expected that P from these three sources would have a similar availability to plants. The results of these and also P desorption experiments were qualitatively similar to those derived from a simple Langmuir model, suggesting that sorption and desorption of P in the soil from the field area occurred at sites on the solid phase with predominantly uniform sorption characteristics.

Marked and largely unexplained variations in several soil parameters monitored over a year obscured the effects of P addition as a maintenance fertilizer application and also the net P transfer by grazing animals. In this and related situations, soil P analysis may not provide a sensitive measure of P status, except in the longer term. A more detailed examination is required to assess the usefulness of routine soil P analysis of hill

soils for advisory purposes. The significant net P transfer from slopes by grazing animals suggests that the complementary roles of grazing management and fertilizer requirements in hill country should also be examined further.

ACKNOWLEDGEMENTS

I wish to express my gratitude to the following people:

Professor J.K. Syers for guidance, direction, and stimulation throughout all stages of this study.

Dr. P.E.H. Gregg for many helpful discussions and comments.

Mr. R.W. Tillman for the development of computer programmes and for many valuable discussions.

The several staff from the Hill Country Section, Soil and Field Research Division, Ministry of Agriculture and Fisheries and Whatawhata Hill Country Research Station who assisted with the field work.

Jan, (my wife), for her encouragement, understanding, and assistance during the term of this study.

Dianne Syers for the excellent and patient typing of this thesis.

Finally, I wish to express my thanks to the New Zealand Ministry of Agriculture and Fisheries who granted me leave to undertake this study.

TABLE OF CONTENTS

	Page
ABSTRACT	i
ACKNOWLEDGEMENTS	iv
TABLE OF CONTENTS	v
LIST OF FIGURES	xi
LIST OF PLATES	xiii
LIST OF TABLES	xiv

SECTION 1

INTRODUCTION	1
------------------------	---

SECTION 2

REVIEW OF LITERATURE

2.1 Soil P	4
2.1.1 Forms of soil P	4
2.1.2 The P sorption process	7
2.1.3 Exchangeable P	11
2.1.4 Assessment of plant-available P	13
2.1.4.1 <u>Isotope methods</u>	14
2.1.4.2 <u>Non-isotope methods</u>	17
2.2 Plant P	19
2.2.1 Factors affecting plant intake of P	19
2.2.2 Factors affecting the rate of <u>P uptake</u>	21
2.2.3 Plant P content	22
2.2.4 Interspecies competition for P	23
2.3 Animal P Intake	25
2.4 P Return to Soil	28
2.4.1 P return via animal dung	29
2.4.1.1 <u>Dung distribution by grazing stock</u>	29
2.4.1.2 <u>Dung excreted and area covered per excretion</u>	31

	Page
2.4.1.3 <u>Dung P content</u>	32
2.4.1.4 <u>Release of P from dung</u>	34
2.4.2 P return via pasture litter	35
2.4.2.1 <u>Types of litter</u>	36
2.4.2.2 <u>Plant senescence</u>	37
2.4.2.3 <u>Release of P from litter</u>	38
2.5 Availability of Returned and Applied P	42
2.5.1 P from organic residues	43
2.5.2 P from fertilizer	46
2.6 Above Ground P Losses	49
2.6.1 P losses in animal products	50
2.6.2 P losses by animal transfer	51
2.6.3 P losses in surface runoff water	51
2,7 General Conclusions	53

SECTION 3

PHOSPHORUS UPTAKE AND RETURN IN GRAZED, STEEP HILL PASTURES

3.1 Introduction	55
3.2 Materials and Methods	57
3.2.1 Trial site	57
3.2.2 Grazing management	61
3.2.3 Sampling procedure	61
3.2.4 Phosphorus uptake	61
3.2.4.1 <u>Pasture dry matter production</u>	61
3.2.4.2 <u>Assessment of P limitation to pasture dry matter production</u>	62
3.2.4.3 <u>Pasture P concentration</u>	63
3.2.5 Phosphorus return	63
3.2.5.1 <u>Total dung dry weight</u>	64
3.2.5.2 <u>Field trial dung for P analysis</u>	64
3.2.5.3 <u>Dung P concentration</u>	65
3.2.5.4 <u>Total litter dry weight</u>	66
3.2.5.5 <u>Litter P concentration</u>	66
3.2.6 Soil phosphorus	68

	Page
3.3 Results and Discussion	68
3.3.1 Phosphorus <u>uptake</u>	68
3.3.1.1 <u>Pasture dry matter production</u>	68
3.3.1.2 <u>Assessment of P limitation to pasture growth</u>	70
3.3.1.3 <u>Pasture species composition</u>	71
3.3.1.4 <u>Pasture P concentration</u>	74
3.3.1.5 <u>Total P uptake by pasture</u>	78
3.3.2 Phosphorus return via dung	78
3.3.2.1 <u>Total dung dry weight</u>	78
3.3.2.2 <u>Estimated dung distribution pattern</u>	82
3.3.2.3 <u>Dung P content</u>	85
3.3.2.4 <u>Total P return in dung</u>	94
3.3.3 Phosphorus return via pasture litter	96
3.3.3.1 <u>Total litter dry weight</u>	96
3.3.3.2 <u>Litter P content</u>	98
3.3.3.3 <u>Total P return in litter</u>	102
3.3.3.4 <u>Estimated pasture utilization by sheep</u>	104
3.3.4 The phosphorus cycle	107
3.3.4.1 <u>Annual uptake and return of P</u>	107
3.3.4.2 <u>Seasonal uptake and return of P</u>	110
3.3.4.3 <u>Dung P and litter P relationships</u>	113
3.3.4.4 <u>Dung P return and net P balance relationships</u>	116
3.3.5 Soil phosphorus	121
3.3.5.1 <u>Total phosphorus</u>	121
3.3.5.2 <u>Soil DIP</u>	127
3.3.5.3 <u>Soil DOP</u>	130
3.3.5.4 <u>Bicarbonate-extractable P</u>	130
3.4 General Discussion	134

SECTION 4

UPTAKE ZONES FOR PHOSPHORUS BY PASTURE ON DIFFERING
STRATA WITHIN A HILL Paddock

4.1 Introduction	142
----------------------------	-----

	Page	
4.2	Materials and Methods	144
4.2.1	Treatments	144
4.2.2	Isotope preparation	145
4.2.3	Isotope placement	147
4.2.4	Soil measurements	148
4.2.5	Pasture harvesting	148
4.2.6	Measurement of ^{32}P activity	150
4.2.7	Processing of results	151
4.3	Results and Discussion	152
4.3.1	Sample preparation comparison	152
4.3.2	Field results	154
4.3.2.1	<u>P uptake after 2 days</u>	156
4.3.2.2	<u>P uptake after 29 days</u>	156
4.4	General Discussion	169

SECTION 5

THE ASSESSMENT OF SOME P SORPTION CHARACTERISTICS OF SOILS FROM THE FIELD TRIAL AREA

5.1	Introduction	173
5.2	Materials and Methods	175
5.2.1	Laboratory experiments	175
5.2.1.1	<u>Measurements of P desorption</u>	175
5.2.1.2	<u>Evaluation of P exchange reactions</u>	177
5.2.1.3	<u>Measurements of P sorption</u>	178
5.2.2	The Langmuir model	179
5.2.2.1	<u>Measurements of P desorption (Langmuir model)</u>	180
5.2.2.2	<u>Fate of an applied 'label' (Langmuir model)</u>	180
5.2.2.3	<u>Measurements of P sorption</u>	181
5.3	Results and Discussion	181
5.3.1	Measurements of P desorption	181
5.3.1.1	<u>Effect of water:soil ratio and extraction period on desorption of P</u>	181
5.3.1.2	<u>Effect of successive extractions with water on desorption of P</u>	184

	Page
5.3.1.3 <u>Effect of antecedent soil moisture content on desorption of P</u>	188
5.3.2 Evaluation of P exchange reactions	191
5.3.2.1 <u>Fate of applied carrier-free ³²P</u>	191
5.3.2.2 <u>Effect of soil P status on net sorption of applied carrier-free ³²P from soil solution</u>	195
5.3.3 Effects of the addition to soil of P from various sources	200
5.3.3.1 <u>Changes in extract ³¹P content</u>	200
5.3.3.2 <u>Changes in extract ³²P content</u>	206
5.4 General Discussion	208

SECTION 6

CHARACTERIZATION OF SHORT-TERM, PLANT-AVAILABLE P USING A DOUBLE LABELLING TECHNIQUE

6.1 Introduction	213
6.2 Materials and Methods	214
6.2.1 Preparation of plants	214
6.2.2 Preparation of soil	216
6.2.3 Sampling and analysis procedures	216
6.2.3.1 <u>Soil analysis</u>	216
6.2.3.2 <u>Plant sampling and analysis</u>	217
6.3 Results and Discussion	218
6.3.1 Soil ³¹ P levels	218
6.3.2 Plant ³¹ P levels	220
6.3.3 Soil and plant ³² P: ³³ P ratios	220
6.4 General Discussion	223

SECTION 7

SIMULATION OF "ABOVE-GROUND" COMPONENTS OF THE P CYCLE IN STEEP, GRAZED PASTURE

7.1 Introduction	227
----------------------------	-----

	Page
7.2 Materials and Methods	228
7.2.1 Effect of stocking rate on the net P balance on each stratum	229
7.2.2 Effect of overall pasture utilization level on the net P balance on each stratum	230
7.2.3 Effect of pasture production level on the net P balance on each stratum	230
7.2.4 Effect of pasture P content on the net P balance on each stratum	231
7.3 Results and Discussion	231
7.3.1 Model validation	231
7.3.2 Model manipulations	233
7.3.2.1 <u>Effect of stocking rate on the net P balance on each stratum</u>	233
7.3.2.2 <u>Effect of overall pasture utilization level on the net P balance on each stratum</u>	235
7.3.2.3 <u>Effect of pasture production and P concentration level on the net P balance on each stratum</u>	237
7.4 General Discussion	237
SUMMARY AND CONCLUSIONS	243
BIBLIOGRAPHY	247
APPENDICES	281

LIST OF FIGURES

	Page
FIGURE A	
Slope:area distribution curves for the total area, for campsites and for tracks in paddocks of both north- and south-facing aspects	285
2.1 Components of the P cycle in grazed, fertilized pasture	5
3.1 Relationship between the concentration of DIP and TP in pasture	77
3.2 Annual total P uptake by pasture and total P return in litter and dung, and net total P balance (kg ha^{-1}) including Standard Errors of estimate for each value	108
3.3 Relationship between total P return in litter and total P return in dung in each season (as % of P uptake by pasture)	115
3.4 Relationship between net total P balance and total P return in dung in each season (kg ha^{-1})	117
3.5 Relationship between net total P balance and total P return in dung in each season (as % of total P uptake by pasture)	120
3.6 Soil total P content ($\mu\text{g g}^{-1}$) on campsites	122
3.7 Soil total P content ($\mu\text{g g}^{-1}$) on 25° slopes	123
3.8 Soil total P content ($\mu\text{g g}^{-1}$) on 45° slopes	124
3.9 Soil DIP (as % of TP)	128
3.10 Olsen P (as % of TP)	133
4.1 Effect of sample size on measured ^{32}P at three levels of activity	153
4.2 Lateral and vertical distribution of relative root activity (%) (Corrected for soil P status at each depth)	161
4.3 Lateral and vertical distribution of relative root activity (%) adjacent to stock tracks (Corrected for soil P status at each depth)	163

	Page	
4.4	Relative root activity at each depth for the north campsite, north 25° slopes, and north 45° slopes, and estimated integrated relative root activity for each soil depth range on north campsite, north 25° slope and north 45° slope	165
4.5	Calculated mid point of lateral root activity distribution at each sampling depth and derivation of the direction of predominant root activity on each stratum	167
5.1	Effect of water:soil ratio and extraction period on desorption of P from north 25° slope soil	182
5.2	Relationship between DIP release per extraction and cumulative total DIP release	185
5.3	Relationship between P release per extraction at a 40:1 water:soil ratio (Langmuir model)	186
5.4	Effect of antecedent soil moisture on desorption of DIP	190
5.5	Fate of carrier-free ³² P applied to north 25° slope soil during subsequent incubation	193
5.6	Change in isotope content during incubation of water and Olsen P extracts from soils of differing P status	196
5.7	Change in isotope content (Relative Specific Activity) during incubation of water and Olsen P extracts from soils of differing P status	199
5.8	Change in ³¹ P content of A water-extractable P (10:1 ratio), B water-extractable P (40:1 ratio) and C Olsen P at various times following addition to soil of water-extractable P from superphosphate, litter, dung and control - nil added P	201
5.9	Change in ³² P content of A water-extractable P (10:1 ratio), B water-extractable P (40:1 ratio) and C Olsen P at various times following addition to soil of ³² P-labelled water-extractable P from superphosphate, litter, dung and control - carrier free ³² P added	207

LIST OF PLATES

	Page
PLATE 3.1 Study area paddock with a north-facing aspect . . .	58
3.2 Study area paddock with a south-facing aspect . . .	58
3.3 Dung and litter collection plot. Dung was collected from the complete (0.2 m ²) plot and litter was collected from only the 8 subplots occupying the central and left side longitudinal thirds	67
4.1 Equipment used for loading gelatin capsules with ³² P, showing capsule holder in position on the mobile platform of the modified beam balance	146
4.2 Wooden template in position above the "hot line" with rods used to make isotope placement holes to required depth	146
4.3 Pasture on a 25 ^o slope plot prior to harvest 29 days following isotope placement. Perspex sheet in position to shield operator from the "hot line" and battery-powered harvesting shears ready for use	149
6.1 Ryegrass grown in sand within nested pots (left side) and showing root development (centre) prior to placement in contact with isotope-labelled and incubated soil (right side)	215

LIST OF TABLES

	Page
TABLE 3.1 Paddock slope composition (% of total area per stratum)	60
3.2 Seasonal and annual pasture production (kgDM ha ⁻¹) from each stratum	69
3.3 Seasonal and annual pasture production from topdressed and untopdressed slope strata (kgDM ha ⁻¹)	72
3.4 Pasture species composition (% by wt.) in each season	73
3.5 Amounts of P forms in pasture in each season	75
3.6 Seasonal and annual uptake of P by pasture on each stratum (kg ha ⁻¹)	79
3.7 Seasonal and annual deposition of dung on each stratum (kgDM ha ⁻¹)	80
3.8 Estimated time required for dung from grazing sheep to completely cover various proportions of each stratum	84
3.9 Dry matter, TDP and TP content of whole, undried sheep dung from "improved" compared with "unimproved" pasture	86
3.10 Amounts of P forms ($\mu\text{g g}^{-1}$) in variously prepared forms of dung as determined by two methods of analysis	87
3.11 Amounts of water-extractable P ($\mu\text{g g}^{-1}$) in variously prepared forms of dung	89
3.12 Water-extractable P removed from oven-dried, crushed dung by both repeated and prolonged extractions	90
3.13 Amounts of P forms in dung collected at each stratum	93
3.14 Seasonal and annual return of P in dung to each stratum (kgDM ha ⁻¹)	95
3.15 Seasonal and annual pasture litter accumulation on each stratum (kgDM ha ⁻¹)	97

	Page	
TABLE 3.16	Amounts of P forms in litter collected at each season	99
3.17	Effect of sample condition on amounts of water-extractable inorganic (DIP) and organic P (DOP) in autumn litter	101
3.18	Seasonal and annual return of total P in litter to each stratum (kg ha ⁻¹)	103
3.19	Estimated seasonal and annual utilization of pasture on each stratum by grazing sheep	105
3.20	Seasonal total P net balance on each stratum	111
3.21	Seasonal total P net balance on each stratum assuming a 3-month delay in availability of P from litter and dung (kg ha ⁻¹)	112
3.22	Organic matter content of soil on each stratum at four sampling dates (% by wt.)	126
3.23	Water-extractable organic P content of soil on each stratum (as % of TP)	131
4.1	Mean ³² P levels (cpm) measured in whole, undried pasture two days following isotope placement in soil at various depths	157
4.2	Relative root activity (%) at various soil depths on each stratum estimated both with and without correction for soil Olsen P values	158
4.3	Soil characteristics on each stratum at trial commencement (13.9.76) and also soil moisture content at final harvest - North aspect	159
5.1	Effect of solution soil ratio on extraction of P (Langmuir model)	183
5.2	Total water extractable P (TDP) from air-dried soil from each stratum of the field trial area and moisture content of each soil during subsequent incubation	189
5.3	Effect of soil P status on fate of applied label and time required to reach equilibrium (Langmuir model)	197

	Page
TABLE 5.4	
Effect of soil P status on fate of applied P (Langmuir model)	203
5.5	
Status of several soil P fractions after 53 days incubation both with and without addition of water-extractable P from pasture litter, dung and superphosphate sources ($\mu\text{g P g}^{-1}$).	205
6.1	
Soil P levels before plant P uptake and soil and plant P levels after plant P uptake ($\mu\text{g g}^{-1}$)	219
6.2	
^{32}P : ^{33}P ratios in soil before plant P uptake and in soil and plant material after plant uptake ($^{32}\text{Pcpm}$: $^{33}\text{Pcpm}$)	222
7.1	
Simulated P uptake and return in paddocks on north- and south-facing aspects (Section 3) incorporating parameter values measured in the field	232
7.2	
Simulated P uptake and return in paddocks of differing slope composition at both full and half maximum stocking rates	234
7.3	
Simulated P uptake and return at maximum pasture grazing utilization levels 65, 70 and 55% of pasture growth on campsites, 25° slopes and 45° slopes respectively in paddocks of differing average slope	236
7.4	
Simulated P uptake and return at (i) pasture production levels equivalent to 80% of those set in Section 7.2.1 and (ii) at a pasture P content of $3500\mu\text{g g}^{-1}$ using the same pasture production levels set in Section 7.2.1.	238

SECTION 1

INTRODUCTION

High animal production from grassland involves first a high degree of utilization of all areas of existing pasture and second an adjustment of soil nutrient status so that higher-producing, high-fertility demanding species can be maintained in the sward.

The extent and permanence of the effects of topdressing an area, whether it be to improve or merely maintain soil nutrient status, depend essentially on the efficiency of the nutrient cycle operating there, i.e., the proportion of total nutrient uptake from any site that is returned by various means. The rate of plant growth and the efficiency of nutrient return both in rate and quantity will be determined by the extent to which pasture growth is removed by the grazing animal and subsequently returned to the site as dung and urine.

Estimates of P utilization have been made by Karlovsky (1962) on flat land under grazing where a steady-state system was assumed to exist and where losses in animal products and transfer were allowed for. On such topography the distribution of animal dung and urine is relatively uniform, although with sheep there is a tendency for the return to be greater nearer camp sites (Hilder, 1966) which receive heavy rates of nutrient return. On hill country these camp sites tend to be even more defined (Gillingham and During, 1973) as variability in the slope and aspect of the land surface modifies grazing and camping patterns. Such camp areas are usually ryegrass dominant and high producing. This contrasts with the remainder of the hill pasture which generally varies widely in species composition (Sears, 1956; Rumball and Esler, 1968) and growth rate (Suckling, 1959; 1975; Radcliffe et al., 1968), often within very short distances. While this variability is most likely associated to a large extent with differences in microclimate

(Lambert, 1973), particularly between aspects, the animal, by both its differential grazing intensity and frequency, and nutrient return to sites of differing surface configuration must also have some effect on vegetation characteristics and therefore also on the efficiency of the nutrient cycle. Thus, it is most likely within a hill paddock receiving an overall uniform rate of nutrient application that there will be a considerable range in the quantity and rate of cycling of that nutrient according to the slope and aspect of the land surface. It therefore follows that the efficiency of nutrient cycling is greater in some situations than others. While these general effects are apparent there is little quantitative evidence of the influence of slope or aspect on any components of the nutrient cycle in hill country or therefore of the full significance of the animal in this situation. Consequently, the complementary role of the grazing animal and topdressing is also not well identified. An examination of nutrient cycling in grazed hill country should first provide evidence of the amounts and rates of nutrient uptake and return, and second an appreciation of the scope for improving the efficiency either through topdressing or stock management. Because P is of major significance to hill country in New Zealand, an evaluation of the P cycle would appear most beneficial. This should be made on a well-topdressed and fully utilized pasture so that effects are measured in a high-producing situation where the animal has its greatest influence on the nutrient cycle.

The aim of the following study was to examine components of the P cycle in grazed hill pasture. This involved assessment of the "above ground" efficiency of the P cycle as affected by the grazing animal, the fate and recovery of applied P and soil properties related to this, the characterization of immediately plant-available P and the zones of predominant soil P uptake by hill pasture:

The study was located on land typical of steep North Island hill country. A general description of North Island hill country is given in Appendix I.

SECTION 2

REVIEW OF LITERATURE

This review attempts to cover major aspects of the phosphorus (P) cycle in grazed and topdressed pasture. The structure of the review will follow the components of the P cycle, as represented in Fig. 2.1.

2.1 Soil P

2.1.1 Forms of soil P

Soil may conveniently be classified as being inorganic or organic, with the rate of supply of available inorganic P, either by weathering of parent material or topdressing, limiting the rate of increase in organic P and associated soil organic matter levels (Walker and Adams, 1958).

Minerals of the apatite group ($\text{Ca}_{10}\text{P}_6\text{O}_{24}\text{Z}_2$, where Z = F, OH, Cl, or $\frac{1}{2}\text{CO}_3$) and in particular fluorapatite, are the major source of primary P in soils. The availability of P in primary minerals depends on the degree of weathering, and thus soil apatite levels tend to decrease with soil age (Syers et al., 1969) and increase with soil depth (Hamilton and Lessard, 1960; Walker and Syers, 1974). Therefore, while primary minerals can provide the major source of plant available P in virgin soils (Syers and Williams, 1977) the rate of weathering is inadequate to provide sufficient P for rapid plant growth. In most soils, other secondary forms of inorganic P (i.e., sorbed and precipitated P) become more important regulators of the P level in the soil solution.

It was earlier considered (Haseman et al., 1950) that the aluminium, iron, and calcium phosphate compounds which were precipitated as fertilizer reaction products constituted an important form of secondary soil P. These compounds have been shown to be unstable and even forms such as variscite ($\text{Al}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$) and strengite ($\text{FePO}_4 \cdot 2\text{H}_2\text{O}$) are unlikely to persist in

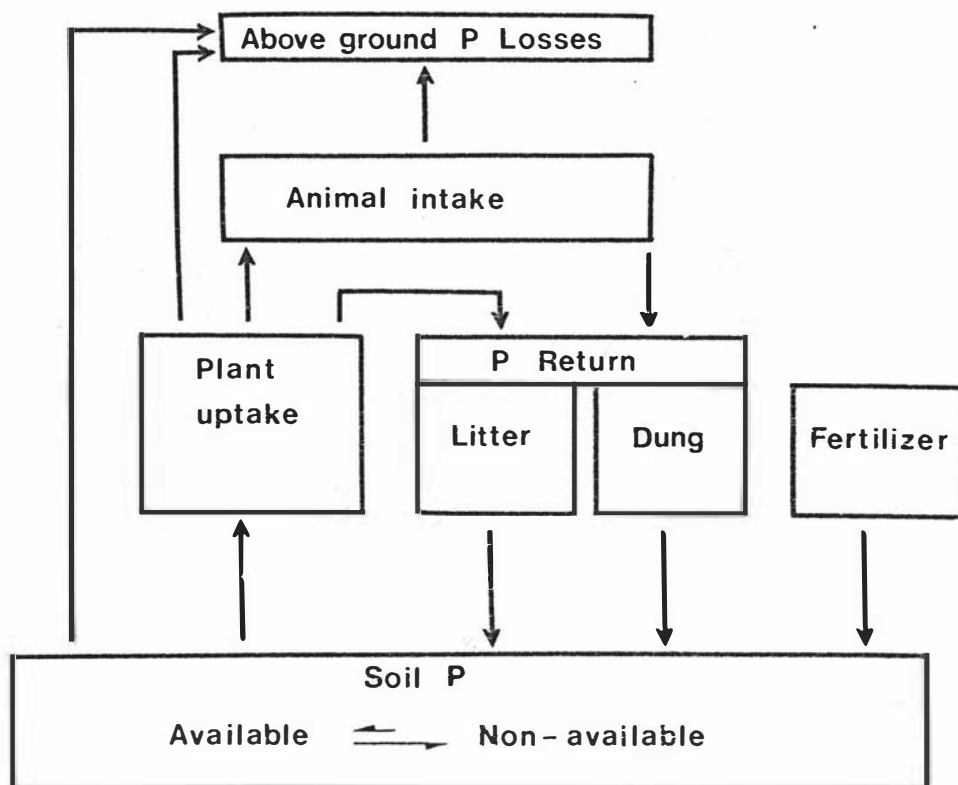


FIGURE 2.1 Components of the P cycle in grazed, fertilized pasture.

soils (Syers and Williams, 1977). Consequently, in developed soils sorption reactions are likely to be the dominant factor determining P concentration in the soil solution.

Two main approaches have been adopted in identifying the major soil components involved in P sorption or retention. The first involves an assessment of P sorption by soil both before and after removing particular components (Williams et al., 1958; Saunders, 1965; Syers et al., 1971). The second involves the use of pure forms of such components and relating results to soils containing known amounts of similar materials. Both methods have demonstrated the importance of short-range order (amorphous) oxides and hydrous oxides of iron and aluminium. These oxides and hydrous oxides generally occur as coatings on clay mineral surfaces (Russell and Low, 1954) and on calcium carbonate. Because the last two components have a relatively low P sorption capacity, such coatings can dramatically increase the P sorption capacity of the soil where this occurs. Data reviewed by Ryden (1975) show that the crystalline oxides and hydrous oxides of iron and aluminium also have considerable sorption capacity although the level represents only about 1 to 10% of that of the amorphous counterparts.

Although net desorption of P from inorganic soil colloids generally provides the predominant supply of P to the soil solution, the mineralization of organic P increases in significance as total soil organic P level rises. Because both organic matter formation and mineralization occur concurrently in soil, the net release or immobilization of P will depend on the dominant process at any one time. The rate of P mineralization is affected by the level of soil organic C and N, and by temperature (Thompson and Black, 1949), especially above 35°C (Eid et al., 1951). The level of P actually available for plant uptake, particularly at low soil P levels, may be markedly affected by concurrent microbial requirements (Syers and Williams, 1977). It has therefore generally been difficult to assess the real importance of organic

P to growing plants, although measured seasonal changes in organic soil P, especially in spring (Dormaer, 1972), suggest that at times net mineralization can be considerable.

2.1.2 The P sorption process

Phosphorus in the soil solution and on the surface of solid phase soil components exists in a dynamic equilibrium (Taylor and Gurney, 1962). Changes in P status of the soil solution by addition or removal of P results in a new equilibrium eventually being established through activation of both P adsorption and desorption mechanisms. Adsorption of P refers to the removal of phosphate ions from solution and their accumulation at a solid surface. Desorption refers to the release of ions from the solid to solution phase.

As the adsorption process continues the structure of the solid phase remains essentially unchanged except for an increase in surface P concentration. In such a system P concentrations maintained in solution at a high degree of surface saturation will be higher than those at a low saturation level. By contrast, precipitation implies a constant solution P concentration, and a constant solubility product.

While adsorption is generally considered to be responsible for the initial rapid loss of added P from the soil solution (Rennie and McKercher, 1959), the usual subsequent slower loss rate has been associated with the so-called "absorption" process. This has also been attributed to the slow reversion of adsorbed P to discrete P compounds (Larsen and Widdowson, 1970; Talibudeen, 1974). Ryden (1975) considers it more related to diffusive penetration or adsorption of P at "internal surfaces". Such P is likely to have a much lower ease of desorption than adsorbed P. The term sorption is less specific and may be used to describe either or both adsorption and absorption of P.

Phosphate release by desorption is generally characterised by a hysteresis effect (Muljadi et al., 1966), implying that sorption is only partly reversible. White and Taylor (1977) concluded that the extent of desorption of added P depended on both the initial P status and the degree of equilibrium attained. Desorption can be increased by increasing pH although Muljadi et al. (1966) consider that sorption from solutions of final P concentration less than $3 \mu\text{gP ml}^{-1}$ was irreversible. While various attempts have been made to explain the desorption mechanism (Kafkafi et al., 1967; Hingston et al., 1974), it is possible that the overall lower recovery of P by desorption may be related predominantly to the "absorption" effect (Evans and Syers, 1971).

The greatest progress toward characterising the P sorption process has been by the use of sorption isotherms. Sorption isotherms are determined for a soil at a given temperature by making various additions of P to a known soil:solution suspension, shaking for a given time, and determining P removal from solution. Of the various shapes or forms of isotherms, the Langmuir or L type is the most commonly used for liquid:solid systems (Ryden, 1975). The Langmuir model has the following equation which when plotted produces a straight line:

$$M_x = \frac{K_1 K_2 C}{1 + K_1 C}$$

where x is the weight of P removed from solution by M weight of soil, C is the equilibrium concentration of P in solution, and K_1 and K_2 are constants related to the bonding energy and sorption maximum, respectively. The equation assumes a limit to sorption when a monolayer of sorbed P occupies the surface. The Langmuir concept therefore also implies that no P exchange occurs, i.e., phosphate ions striking occupied sites are reflected (Ryden, 1975).

This equation has been used widely to describe and interpret P sorption data (Cole et al., 1953; Shapiro and Fried, 1959; Syers et al., 1973). A general problem encountered, because of the slow absorption process, is the definition of a true equilibrium concentration. In this respect, Ryden and Syers (1975b) suggest that a solution or "support medium" of high ionic strength should be used in order to increase the P sorption rate and so reduce the equilibration period. They also suggest that determination of the relationship between solution P concentration and the reciprocal of time is a useful technique which permits the graphical derivation of the equilibrium concentration (at $1/t = 0, t = \infty$) without the need for prolonged experiments.

Application of the Langmuir equation to the interpretation of P sorption by soil and soil components has led to conclusions that the overall P sorption relationship may be either curvilinear (Gunary, 1970; Bache and Williams, 1971) or comprised of two (Shapiro and Fried, 1959; Griffin and Jurinak, 1973; Syers et al., 1973) or three distinct straight line portions or "regions" (Muljadi et al., 1966; Karim et al., 1973; Ryden and Syers, 1975a), depending on the P concentration measured and to some extent on the scale of plotting results and the number of data points used.

By measuring sorption over a wide range of P concentrations, Ryden and Syers (1975a) were able to demonstrate the existence of three linear regions, each relating to a particular concentration range, i.e., 0 to 0.07, 1.5 to 25, and 32 to 650 mol^{1-1} P for regions I, II, and III, respectively. The involvement of three such regions suggests the existence of three types of sorption sites and that as further P is added these tend to be filled in turn. Region III sorption is considered to occur at the phosphated surface generated by sorption in regions I and II.

Ryden and Syers (1975a) described three different sorption mechanisms which were considered to occur in the three P concentration ranges. Later

Ryden et al. (1977a) proposed that in both regions I and II chemisorption occurred but that a "more-physical" sorption occurred in region III, the latter being a less strong bonding more dependent on the ionic strength of the contacting solution. This does apparently involve electron transfer and so cannot be defined as purely physical sorption. The distinction between physical and chemisorption is often made but not always defined. Hayward and Trapnell (1964) consider that during chemisorption electron transfer occurs between the solution and solid phase similar to that of bond formation in a chemical reaction. With physical sorption no electron transfer occurs.

Sorption occurring in region I is characterized by a high sorption energy and also a rapid removal from solution of almost all added P (Ryden, 1975). Elimination of such sorption sites may be possible by saturation with P, as would occur on well-topdressed soils, thus producing an associated shift of the predominant P sorption into regions II and III. In support of this Bache (1964) observed that increasing additions of P were sorbed with lower energy and were therefore more readily desorbed. White and Taylor (1977) considered that bonding energy decreased exponentially with P sorption site coverage. This more-readily desorbed P, however, may comprise only a small, rapidly diminishing fraction compared with the bulk of more firmly-sorbed P released at a slower, more constant rate, especially in high P-sorbing soils (Fried and Shapiro, 1956).

A significant factor influencing P sorption is that of soil pH level (Saunders, 1958, 1965). Liming affects the number of protonated sites available which are involved in sorption in region I (Ryden and Syers, 1975a). Region III sorption is also pH dependent and thus an increase in P desorption with increase in soil pH will most likely reflect the reversibility of region III sorption. Muljadi et al. (1966) considered that desorption from regions I and II would occur only at high pH level.

The P concentration in the soil solution of field soils is generally of the order of that associated with P sorption in regions I and II (Barber et al., 1962). The availability of P to the growing plant in these situations may therefore be dependent on a high pH of the soil solution between the desorbing surface and the plant root. Alternatively it is possible that the release of P may be aided by organic anions released from plant roots (Nagarajah et al., 1968).

2.1.3 Exchangeable P

Total exchangeable soil P represents the quantity in equilibrium with P in solution and therefore is important as a measure of the P which is potentially plant available.

The phenomenon of isotopic exchangeability was first utilised by McAuliffe et al. (1948) to determine total exchangeable P. This was described as the 'E' value. While the technique can be similarly used to determine the total exchangeable quantity of any soil nutrient, Fried (1964) contended that the 'E' value should be restricted to exchangeable P only.

Exchangeable P is generally estimated after addition of isotope to a water (or neutral electrolyte) and soil mixture at equilibrium and measurement of both the solution ^{32}P activity and ^{31}P level after an equilibrium period of time (t):

$$E = \text{Total } ^{32}\text{P added} \times \frac{^{31}\text{P in solution}}{^{32}\text{P in solution}}$$

The process of heterogenous (two phase) exchange when a tracer is added to soil solution is characterized by an initial rapid exchange between the tracer in solution and the surface of the solid phase (i.e., the adsorption process) followed by a deeper, slower penetration of the tracer into the lattice of the solid (i.e., the "absorption" process). As with

the application of the Langmuir equation, the validity of the E estimate is dependent on a true equilibrium having been reached. Therefore t should be as large as possible. Mattingly and Talibudeen (1960) suggested that for routine work, the amount of P exchanged in 20 hours can be taken as the rapidly exchanging P and that exchanged in 170 hours as the total isotopically exchangeable P.

Any factors modifying the rate of net P sorption from the soil solution will obviously affect the estimate of exchangeable P made at any time. Estimates of isotopically exchangeable P were found to decrease (Mattingly and Talibudeen, 1960) as soil:solution ratio increased, but the effect was negligible at soil:water ratio of less than 2:100. Similarly Barbier et al. (1954) reported that for a 120-fold change in ratio, the "estimated labile P" after 24 hours of shaking, varied by only 15%. This effect diminished at longer equilibration periods.

Addition of inorganic P slows the net rate of decline in level of isotope in the equilibrating solution (Talibudeen, 1957), i.e., equilibrium is reached more slowly. This would be expected from the greater amount of P involved in exchange but may to some extent also be associated with the recorded tendency for organic P levels to fall after inorganic P additions (Enwezor, 1966; Smith, 1966). Prolonged mineralization of organic P would be a factor in the delayed attainment of an equilibrium.

Mattingly and Talibudeen (1960) showed that the form of added P could be important. When water-soluble P was added to either calcareous or acid soils, both the total exchangeable P and the rapidly exchanging portion of this fraction increased. Addition of "insoluble" forms of P (e.g., apatite) to calcareous soils caused little change in isotopic exchangeability of soil P. Rock phosphate, basic slag, and superphosphate, however, all had similar effects when applied to soils of pH 4.9 to 5.4.

Fertilizer materials that shifted the cation balance in non-calcareous soils in favour of monovalent cations were found to increase the rate of exchange of slowly-exchanging P (Mattingly and Talibudeen, 1960). The effect was relatively small and attributed to the decrease in Al^{3+} activity at the soil:water interface when changing from a divalent to a monovalent cation-dominated soil.

Sorption of added P also tends to be lower under reducing than under oxidizing conditions, as demonstrated by the measured increase in inorganic P in lake bottom waters following oxygen depletion (Mortimer, 1941, 1942); a feature explained by the transformation of oxyferric hydroxide to less reactive ferrous compounds.

Soil solution equilibrium P concentrations tend to increase with temperature (Aslyng, 1950). Arambarri and Talibudeen (1959) also recorded increases in the equilibrium concentration and the rate of exchange of the "slowly labile" P in soils of low P status with a temperature rise from 35° to 45°C. Soils of higher P status, however, did not exhibit this effect. The increase in surface energy associated with a temperature rise would be expected to reduce the stability of sorbed P. Singh and Jones (1977) therefore concluded that the effect of rising temperature was to increase P desorption rate relative to adsorption rate.

2.1.4 Assessment of plant-available P

There appears to be no simple and direct relationship between labile or exchangeable P, and the various chemical forms of P in the soil. The exchangeability of the various fractions generally decreases in the order water-soluble P, Al-P, Fe-P, Ca-P. The predominant form in a soil, however, may play the greatest role in exchange. For example, in a study of rice soils in Sri Lanka, Al-Abbas et al (1967) concluded that because Al-P was at very low levels Fe-P contributed most of plant requirements.

In non-calcareous soils, where Al-P and Fe-P predominate, these probably provide the greatest source for plant uptake. In soils of pH greater than 7, plants probably use mainly Al-P and Ca-P (DuPlessis and Burger, 1966).

The incomplete identification of plant-available P in soil, and conditions affecting the source and form of this fraction, continue to limit a better understanding of plant P requirements. This in turn has particular relevance to the form of P fertilizer that could most efficiently meet these requirements.

Assessment of plant-available P has been by two main methods:

1. Isotope Methods which involve measurement of P uptake by plants and, by means of isotopic activity, relating this directly to the soil from which it was obtained.
2. Non-Isotope Methods which involve extraction of soil P and relating this to plant P uptake or dry matter production as a means of developing a routine assessment for plant P requirements.

2.1.4.1 Isotope methods

The phenomenon of isotopic exchangeability has been used to advantage in several ways. Larsen (1950) was the first to define plant-available P using this method. The concept is similar to that proposed by McAuliffe et al. (1948) to define 'E', the total exchangeable P in soil. Instead of measuring the P level of a given extract, however, Larsen used the P uptake by a plant growing in the soil to derive the 'L' value or labile soil P level, i.e. :

$$L = \frac{{}^{31}\text{P}_{\text{ plant }} \times {}^{32}\text{P}_{\text{ added }}}{{}^{32}\text{P}_{\text{ plant }}}$$

The ${}^{32}\text{P}$ may be applied to soil either with, or without, an associated

fertilizer. The estimate of L should be made after an initial equilibration period, particularly if a fertilizer is applied, because L should be constant throughout the period of plant growth. The measurement is therefore generally made after a number of harvests have been taken, e.g., Larsen and Gunary (1964) calculated L values from the 4th cut of ryegrass. In some cases L values were still increasing at the 5th harvest. Pre-incubation of the isotope for up to 2 months before sowing seed had virtually no effect on the above situation. The rise in L value was attributed to improving root exploration of non-equilibrated P over the trial duration. This may also be associated with a phenomenon noted by Larsen and Cooke (1961) and others that ^{32}P in fertilizer tends to inhibit P uptake by plants, i.e., uptake tends to be from areas of low specific activity. This does not invalidate the L value technique but does suggest that in such studies the isotope and soil must be thoroughly mixed.

In a recent assessment of the technique, Dalal and Hallsworth (1977) reported that estimated L values were comparable with E values on low P-sorbing soils but the relationship did not persist on high P-sorbing soils where E was much higher. On such soils, E was considered to be relatively over-estimated due to the greater proportion of sorbed compared with exchanged P, relative to that in low P-sorbing soils. A better relationship existed between L and E calculated by the inverse dilution method (E_{ID}) of Mekhael et al. (1965). In this method, ^{31}P is added to a soil previously incubated with a carrier-free isotope. The soil solution is analysed for both ^{31}P and isotope content before and after ^{31}P addition.

Another widely-known method of defining available soil P is by derivation of the 'A' value, introduced by Fried and Dean (1952a). Although in practice it can be somewhat similar to the L value approach it is conceptually quite different. The original derivation is based on the assumed definition that if a plant is confronted with two sources of a

nutrient, uptake will occur in direct proportion to the amounts available. Therefore, if a fertilizer is added to a soil, plant P uptake should extract equal proportion from both soil and added P. Fertilizer is used therefore merely as a known standard source. For greatest accuracy, measurement should be over as short a period as possible, in direct contrast to the L value requirement. A is calculated as follows:

$$A \text{ value (e.g., total available soil P)} = \text{plant P uptake from soil} \\ \times \frac{\text{total fertilizer P applied}}{\text{plant P uptake from fertilizer}}$$

Although in this instance the A value represents the available P in a soil it can be used to derive any nutrient availability from any source.

The original concept inferred (Dean, 1954) that A values, or estimated available P levels, for any one soil, should remain constant over a range of P fertilizer application rates, i.e., as applied P rate increased so did total plant P uptake and fertilizer P uptake with the uptake of soil P remaining constant. In this P responsive situation, the proportional uptake of fertilizer P was also assumed to remain constant. As initially stated (Fried and Dean, 1952b) the A value can be affected by such things as the method of adding P to the soil, or the chemical form of added P. Another influence is the relative availability of other nutrients, e.g., nitrogen, which may induce variable soil P uptake (Sheard, 1974). In such a situation, however, A values may provide a useful index of this variability (Smith and Legg, 1971).

The A value concept has subsequently been applied to soils of varying P status and also by incorporating the use of only a single rate of isotopically-labelled fertilizer. In non-P responsive conditions (i.e., where total plant P uptake remains constant over a range of fertilizer application rates), and in the use of isotopic dilution to derive A, the original assumptions do not apply (Smith and Legg, 1971). Where total

plant P uptake is constant with differing P application rates the level of soil P uptake decreases as applied P rate increases and the level of applied P taken up by the plant also increases. The calculated A value, however, remains constant. In fact the high P status, non-P responsive soil appears to be the only situation where reasonably constant A values can be obtained (Terman and Khasawneh, 1968). In low P soils, A values have been found to increase with increased P application rates (Terman and Khasawneh, 1968). The increased soil P uptake in these conditions has generally been interpreted as due to greater root development and exploration of available soil P by more vigorous growing plants. In soils of more moderate P status variable, but usually increasing, A values have been determined.

Both the A and L value methods of estimating plant-available P appear to have limitations. The L value technique depends first on a true equilibrium between the isotope and soil P being achieved and second on the plant fully exploring the soil. This requires relatively long-term experiments. The short-term A value technique only seems to be applicable in determining plant-available P on some soils of high P status. This emphasizes the difficulties associated with relating P taken up by a plant to that available in the soil, even when isotopes provide a means of identifying such P.

2.1.4.2 Non-isotope methods

Many methods of extracting soil P have been correlated with plant uptake as an empirical means of defining the 'plant-available' pool. Anion exchange resins have given promising results in this respect (DuPlessis and Burger, 1966; Bache and Rogers, 1970; Balleaux and Peaslee, 1975; Brewster et al., 1975). The P removed by mildly acid (Truog, 1930) and alkaline (Olsen et al., 1954) extracts of soil have also been correlated with plant growth and therefore identified as representing the "plant-

available" status of the soil. Of these two procedures the Olsen bicarbonate test is considered to provide the more useful estimate of plant availability (Syers, 1974) because of its ability to desorb P, compared with the dissolution of predominantly calcium-bound phosphate, if present, in the Truog reagent.

Attention has also been given to the use of distilled water alone as an extractant (Bingham, 1949; Nelson et al., 1953; Martin and Mikkelsen, 1960; Hagin et al., 1963; Sissingh, 1969). This is now used as the basis for determining P requirements of arable soils in the Netherlands (van der Paauw, 1971) and more recently with acid and organic soils in California (Syers, pers. comm.). For grassland soils, van der Paauw found water-extractable inorganic P, P_w, (60:1 water:soil ratio by volume shaken for 1 hour at 20°C after prewetting for 22 hours) to give a less satisfactory correlation with plant P uptake than did the so called PAL method of Egnér et al. (1960) which employs a stronger extractant (e.g., 1% citric acid or an ammonium lactic acid mixture). This was explained in terms of the greater intensity of P uptake from densely-rooted, superficial pasture soil layers than from crop soils. Similarly, in evaluating several soil tests Daughtrey et al. (1973) concluded that dilute acid (0.5N HCl + 0.025N H₂SO₄) extractable P was the best indicator of potential soil P supply from acid, organic soils. They found, however, that the 12th extract with water was better related to the response of crops to applied P.

Recently Ryden and Syers (1977), developed a water extraction technique which relates plant available P to the "more-physically" sorbed P and therefore promises to be more useful than many previous empirical approaches. The procedure extracts relatively more P than the P_w technique (van der Paauw, 1971) and so incorporates a greater capacity estimate or

measure of more than just the immediately plant-available P.

Using this technique in pot trials Luscombe (1976) was able to demonstrate the superiority of water-extractable P over both Olsen and Truog P as a relative measure of plant availability, although the relationship deteriorated with increasing harvests.

Considerable progress has been achieved in recent years in describing and defining the process of P sorption and in identifying the soil components involved. The use and development of sorption isotherm techniques and isotopic exchange theory have been significant in this achievement. Progress has been less satisfactory in defining plant-available P and in particular the relationship between immediately and potentially available forms. In this respect, a better understanding of both the form of immediately plant-available P and the P desorption process is still required.

2.2 Plant P

In general terms the uptake of P from the soil by a plant depends on both the root distribution pattern and the "plant-available" P status of the soil. Between these two factors, however, are a number of largely unknown and little understood reactions relating to the release of nutrients from solid to solution phase, the means by which they are brought to the root surface, and the mechanism of entry into the plant root. Where P is non-limiting however the rate and level of P uptake will be determined by other, predominantly environmental factors.

2.2.1 Factors affecting plant intake of P

Lewis and Quirk (1967a) proposed that there are three mechanisms by which soil nutrients are brought to the root surface. These are mass flow,

diffusion, and root interception. Of these root interception has been regarded as the least important and conversely both mass flow and diffusion may be of greatest importance in differing situations. Omanwar and Robertson (1970) considered mass flow to be the most important process of P transport to roots in soils recently treated with P fertilizer. In untreated soils the major process was considered to be apparent diffusion. Apparent diffusion, as defined by Lewis and Quirk (1967a), is related to the Diffusion Coefficient (D_p) of a soil by considering the proportion of available P present in solution:

$$\text{Apparent Diffusion } (D_e) = D_p \frac{\text{solution phase P}}{\text{total available P}}$$

D_e then is related to both capacity and intensity factors characterising soil P availability. Similarly Olsen and Watanabe (1963) earlier concluded that the rate of P uptake was related to the soil diffusion coefficient (D_p) and (b) the slope of the "phosphate capacity" line, i.e., rate of uptake $\propto bD_p$. This relationship explained the differences they recorded in P uptake by corn seedlings from clay and sandy soils with initially similar soil solution P concentrations.

Transfer of P into the plant root is apparently a function of the P concentration of the soil solution (Barley, 1970; Thomas and Peaslee, 1975). White (1973) hypothesised that the influx rate of P into root cortical cells was regulated by the turnover rate of the inorganic P pool in the cytoplasm and by the rate of transport of inorganic P to the shoot. This depended on the growth rate of the plant species and the supply of other essential nutrients. This suggests that shoot growth may regulate the uptake of P, which is contrary to the conclusions of Jung and Barber (1975) who found that trimming of corn roots did not increase P flux into the remaining roots. They therefore considered that P uptake was influenced more by the root than the shoot demand; a conclusion also reached by Newman and Andrews (1973).

While root hairs may aid plant P uptake they by no means provide the only access. Root hairs on wheat have been implicated in P uptake because the zone of soil P depletion extended to about 1 mm, the length of root hairs around the root (Lewis and Quirk, 1967b). Bole (1973) however, concluded that P uptake by wheat was not related to root hair density since these only increased from 45 to 60mm⁻¹ in a soil of low compared with adequate P status, respectively. By comparison, P uptake by rape, which has virtually no root hairs, was 2 to 6 times that of wheat. Ectotrophic mycorrhizas also provide a means of significant P uptake and may be of particular advantage to species which have relatively few root hairs. This advantage has been shown to be due to greater uptake of available P rather than any ability to extract non-exchangeable P (Bielecki, 1973). The movement of P within the plant can be very rapid as demonstrated by Troughton (1960). Uptake of ³²P by one root of a ryegrass plant was so rapid that within 6 hours ³²P was present in all tillers.

2.2.2 Factors affecting rate of P uptake

Of the many interrelated factors that influence plant growth perhaps the most important is nutrient availability. The effects of mineral nutrition on plant physiology were reviewed by Pirson (1955) and Bouma and Dowling (1966). On more weathered and leached soils the nutrient most frequently limiting plant growth under untopdressed conditions is P. Maximum growth and P uptake, however, can only be obtained when temperature, light, and moisture conditions are also at an optimum and the plant is in a physiological condition capable of taking greatest advantage of the situation.

The effect of temperature on the growth of various temperate pasture species has been reported by Mitchell, 1956a and b; Mitchell and Lucanus, 1962; Gibson, 1967; Baker and Jung, 1968; Cooper and Tainton, 1968;

Garwood, 1967; Peacock, 1970; and Hoglund and Brock, 1974. Similarly, the influence of light or daylength was examined by Sprague, 1943; Black, 1955; Mitchell and Coles, 1955; Troughton, 1960; Patel and Cooper, 1961; Grant, 1970; Evans, 1971; and Vartha 1973. The other major environmental factor, that of moisture availability, has also been researched in detail. Some of the effects of limiting moisture level on plant growth have been reported by Finn and Mack, 1964; Garwood, 1968; Brown and Blaser, 1970; and Colman, 1971.

The effect of plant shading and of different levels of temperature and moisture on the survival and performance of root nodule bacteria associated with temperate legume species has also been studied (Butler et al., 1959; Marshall, 1964; Gibson, 1967; Wilkins, 1967; Small and Joffe, 1968).

In the presence of adequate moisture, light, and temperature, plants will grow as fast as the supply of the most limiting nutrient allows. The Mitscherlich equation was among the first mathematical expressions of this assumption. In recent years less emphasis has been placed on this single factor approach in recognition of the complex conditions influencing plant response. A review of the more commonly used models has been published by Heady (1960).

2.2.3 Plant P content

The concentration of P in plant material is affected by plant genus, type of tissue, age of tissue, and age and physiological condition of the plant. In general, older plant tissue is of lower P content than young leaves, largely because of 'carbohydrate dilution' but also as a result of some translocation of P to reproductive or more vigorously growing tissue, especially when plants are in P deficient conditions.

McNaught (1970) proposed tentative 'critical' nutrient levels for use

in predicting fertilizer responses by actively growing ryegrass (Lolium perenne, L) and white clover (Trifolium repens). The minimum P concentration in plant tissues for maximum yields were considered to be in the order of 2800 to 3600 μgPg^{-1} for ryegrass and 3000 to 4000 μgPg^{-1} for white clover. A 'safe excess' with luxury P uptake, however, may be as high as 7000 μgPg^{-1} (McNaught pers. comm.). Most grasses have similar needs to ryegrass, although paspalum (Paspalum dilatatum. Poir) usually has lower levels of most nutrients.

Correction of an N or S deficiency tends to increase plant P levels through a 'synergistic effect' in increasing P uptake efficiency. This is in contrast to the effect on plant K concentration which is diluted by increased growth (McNaught, 1970).

2.2.4 Interspecies competition for P

The competition between species for moisture and nutrients (below ground) and for light in particular above ground, depends essentially on their own individual growth form in relation to the other species present. In a pasture situation this also depends on how the plant form is allowed to be expressed by the grazing system applied to the sward. The effect of different defoliation regimes on inter-species competition has been studied by Brougham, 1959 (ryegrass and white clover); Harris and Brougham, 1968 (ryegrass and red and white clover); Harris, 1971, 1973 (ryegrass and white clover); Harris and Thomas, 1972 (browntop and ryegrass); O'Brien et al. 1967 (ryegrass and meadow fescue); and Donald, 1956 (review).

The relative competitive abilities of grasses and legumes for P is an important consideration in maintaining a desirable pasture species balance, particularly in situations where no artificial nitrogen is supplied to maintain grass growth. The differing requirements of pasture

species for P may be expressed by differences in growth of tops, roots, the whole plant, or top/root ratio, as noted by Ozanne et al. (1964). This can obviously affect the subsequent botanical composition of the pasture.

In non-P limiting situations the P concentration of legumes is higher (McNaught, 1970), largely due to higher associated N levels, and the uptake of P is greater (Drake and Steckel, 1955; Probert, 1972), especially as temperature increases (Valentine and Barley, 1976). Nye and Foster (1956) concluded, however, that there was little evidence that legumes achieved this by any ability to use non-exchangeable P.

In situations of moisture shortage, it appears that grasses with their more intensive root network have an advantage over legumes. Jackman and Mouat (1972) showed that an increase in soil moisture tension adversely affected white clover more than browntop and that this effect was greatest in high P-"fixing" soils that also easily develop a high moisture tension. In an earlier study, Mouat and Walker (1959) showed browntop to be a stronger competitor for P than either ryegrass or cocksfoot, again a reflection of the more intensive root network of the finer-leaved grass. In support of this Nye and Foster (1958) concluded that differences in P uptake by various species was due to differences in root numbers and root tips rather than any other ability. Root distribution was also studied by Haynes and Sayre (1956) in relation to maize growth. They concluded that at increasing root density, water stress preceded shortage of an immobile nutrient such as P.

Both grasses and legumes appear to have similar mechanisms of P uptake therefore those plants with a fine and dense root network will most efficiently utilise available soil P. In a pasture situation, where legumes are the main source of N for associated grasses, there is an obvious

need to develop clovers with extensive and fine root systems. As suggested by Godwin and Wilson (1977), however, examination of the effects of greater root hair numbers and mycorrhizal association in promoting P uptake, and root cation exchange capacity, as it adversely affects P uptake, are factors which should also be examined in the programme of selecting plants for increased efficiency of P use.

2.3 Animal P Intake

In New Zealand, the nutrient intake by a grazing animal is derived almost entirely from the pasture species consumed. In some locations and at certain times of the year some supplementary feeding or supply of mineral concentrates may provide another marginal source. In addition Healy (1967) has shown that soil ingestion may contribute significant amounts of certain nutrients. Animal intake of P, however will be governed largely by the pasture available, its P concentration, and the level of grazing utilization.

Young pasture plants contain higher nutrient concentration levels than those in a senescent or flowering condition. Such young plants provide a more rich source of crude protein than older plants and are both more palatable and digestible (Minson et al., 1960). They therefore tend to be selectively grazed (Blaser et al., 1960) and more so by sheep than cattle (Meyer, et al., 1957). In terms of obtaining the greatest benefit from grown pasture, however, it is important that stock are induced to graze all plant material and thus practice a minimum of selective grazing, even though this generally results in reduced performance per animal (Blaser et al., 1960) and a higher grazing:ruminating time ratio (Lofgreen et al., 1957).

The role of grazing management, therefore, is to provide the best

compromise between production per animal and production per unit area of land. Selective grazing precedes an eventual accumulation of rejected senescent and dead plant material that ultimately reduces the available grazing area and may only be removed to any extent by subsequent heavy grazing pressure in times of slow pasture growth or, where possible, by mowing. The best grazing management will induce maximum growth of the most productive and desirable pasture species but will also ensure that the greatest proportion of these will be grazed by stock (Kydd, 1957), i.e., pasture utilization should be as high as possible.

It is recognised that the better dairy farmers in New Zealand obtain the most efficient pasture utilization and probably achieve levels of about 80% (Smetham, 1973). Brougham (1966) estimated that the national average for pasture consumed by dairy stock was only about 3370 kg DM ha⁻¹ annually. This suggests that if, as he assumed, 11,240 kg ha⁻¹ of dry matter is produced over a wide range of pastures, that more than two-thirds of the grass grown is not eaten. Although no account of feed requirements by replacement stock or by cows not in milk was made, this correction would not greatly change the estimate. This was a similarly low level to that estimated by Eadie (1970) for British hill country (20 to 30%). These utilization levels, however, are low in relation to other estimates, e.g., 63% by half-bred hoggets (Herriott and Wells, 1963) and 50% for grazed British pastures (Davies, 1960). Using faecal output and feed:faeces indices, Wallace (1956) calculated that dairy cows could obtain 3630 kg of digestible organic matter from 5450 kg of pasture dry matter.

The merits of various grazing systems in achieving maximum animal production per unit of land have been propounded for many years. The two basic systems used are set stocking, where animals are relatively lightly stocked over most of a farm and moved only infrequently for special purposes,

and 'rotational grazing' where stock are concentrated into one or more mobs and moved from paddock to paddock after spending from a day to a week or more in each.

Freer (1959) reviewed a number of continuous and intermittent grazing experiments in various parts of the world and found little difference in results from either system. This is perhaps not surprising considering the wide range in management systems employed under each technique. More recently it has been shown that stocking rate has to be reasonably high before rotational grazing showed to advantage (Kissock, 1966, 16 ewes ha⁻¹; McMeekan, 1960, 3.0 cows ha⁻¹; Lambourne, 1956, 20 ewes ha⁻¹). This was generally not associated with any difference in total pasture production (McMeekan 1960; Campbell, 1966) which was not significantly affected by grazing management or stocking rate. Increased stocking rate was reflected in much better pasture utilization, particularly under rotational grazing (Campbell, 1966) and this was the feature responsible for the animal production difference between the grazing systems at high stocking rates.

While pasture growth in the above trials was not affected by grazing method very high pressure applied by frequent rotational grazing (e.g., a 7-day interval) can depress yield (Campbell, 1970). This observation was supported by Brougham (1959) who subsequently (Brougham, 1970) emphasized that hard grazing regardless of season is not efficient and should be adjusted for the requirements of desirable species. On this basis he outlined a model management system for a ryegrass-white clover dominant pasture.

The degree of response of a pasture to any grazing method will depend essentially on the species composition. Desirable species for a rotational grazing system must react favourably to hard grazing and long spelling. It has been suggested therefore (Smetham, 1973) that ryegrasses

and legumes should occupy more than 30% of the sward. The obvious shortage of these species in most New Zealand hill pastures (Brougham et al., 1973) may partly explain why rotational grazing systems have not yet been widely accepted in these areas. Conversely, it could be argued that these species are not allowed to fully express themselves because of the predominantly set stocking systems in use.

The application of intensive rotational grazing systems, such as proposed by Smith and Dawson (1976), to hill country sheep and cattle farms is not easy because these are generally on less productive soils and therefore large paddocks are required which in many cases are topographically complex. Larger numbers of animals are involved and at certain times of the year, e.g., during lambing, problems of mismothering and unthriftiness in stock can appear if a rotational grazing system is maintained (Suckling, 1959). Consequently, on the majority of sheep farms a combination of some form of rotational grazing for part of the year and set stocking at other times is used.

An illustration of the annual total P intake by grazing animals can be provided by a simple calculation. If a pasture of $10,000 \text{ kg DM ha}^{-1}$ has a mean P content of $4000 \mu\text{g g}^{-1}$ and is efficiently grazed so that 80% is consumed by stock, this will represent a total intake by animals of 32 kg P ha^{-1} annually. Variation in the efficiency of redistribution of this quantity of P obviously could greatly affect subsequent topdressing requirements.

2.4 P Return to Soil

In a grazed pasture nutrients taken-up by plants can be returned to the soil in either of two ways:

1. In animal excreta after being consumed by stock. The nutrient concentration of either dung or urine depends on the relative rate of incorporation into animal products. The level of excretal return to the grazed pasture will be affected by camping tendencies or other management or behaviour patterns that tend to result in dung and urine depositions on non-productive sites.

2. As a constituent of ungrazed plant material that has been either inaccessible to, or avoided by animals and which subsequently collapses or is trampled to the soil surface as pasture litter.

2.4.1 P return via animal dung

The excretion of P by animals occurs almost entirely via dung, in contrast to N and K which are largely excreted in urine. For example Peterson et al. (1956b) reported that the nutrient contents of dung and urine from grazing cattle were N = 0.38% and 1.10%, P = 0.08% and 0.004%, and K = 0.18% and 0.96%, respectively. Allowing also for the area covered per excretion, the P application rate in dung was calculated to be equivalent to 398 kg ha⁻¹ whereas that in urine was only 17 kg ha⁻¹. Similarly, Sears and Newbold (1942) estimated that only about 1 to 2% of ingested P was excreted in urine. Urinary P can therefore be disregarded as providing any significant pathway for P return to the soil.

The value of dung as a source of plant-available P will largely depend on the distribution pattern which will affect the quantity of dung deposited at any site, within the grazing area, and also on the P content and release of this P from dung.

2.4.1.1 Dung distribution by grazing stock

A major factor influencing dung distribution patterns is the type of grazing stock. Sheep tend to develop permanent, defined camp or

resting areas where heavy rates of dung and urine are deposited. With cattle, campsites are usually freshly chosen at each grazing although some areas (e.g., near shelter or gateways) always tend to receive relatively high levels of excreta. Both grazing and dung return patterns of cattle and sheep, however, can be influenced by proximity to roads (Gardener and Centeno, 1966), supplementary feed distribution patterns (MacDiarmid and Watkin, 1972), and water supply (Peterson et al., 1956a).

Sheep camp sites are usually small in area and, on relatively flat paddocks, are located on an elevated portion or adjacent to shelter. Hilder (1966) reported that about 30% of the total faecal output of Merino ewes was concentrated on less than 5% of the grazing area. This proportion was similar to that estimated by May et al. (1968) as comprising the camp area. On moderately steep hill country, Gillingham and During (1973) found the campsite or 'A stratum' to occupy 6.4% of the grazing area.

Although it is recognised that campsites receive frequent applications of dung and urine, as evidenced predominantly by higher soil P and K levels than in the surrounding paddock (Hilder and Mottershead, 1963; Gillingham and During, 1973), there has been little attempt to quantitatively determine dung distribution patterns on the remainder of a grazed paddock. The dung return interval (i.e., the period elapsed between successive applications of dung) for any one unit area of land can readily be calculated from a knowledge of the animal stocking rate, the number of animal excretions per day, and the area covered per excretion if a non-overlap distribution pattern is assumed. That is if it is also assumed that the total paddock is covered by one excretion before any part is covered by a second. This may provide a useful approximation over short intervals but is progressively less accurate with increased time. In one of the few reported attempts to define dung and urine distribution patterns, Peterson et al. (1956a) concluded that

a negative-binomial function would best describe the excretal distribution pattern of grazing cows. They considered however, that over a 1 to 3 year period an assumed Poisson distribution would provide reasonable accuracy. Both dung and urine distribution patterns were similar, a conclusion also reached by Hilder (1966).

2.4.1.2 Dung excreted and area covered per excretion

Many measurements have been made of the excretion of dung by grazing stock. This has involved determinations of the number of daily excretions and the weight of dung in each. Estimates of the average daily total defaecations by cattle have variously been estimated as 10.6 (Weeda, 1967), 12 (Johnstone-Wallace and Kennedy, 1944; Goodall, 1951; Hancock and McArthur, 1951; Peterson et al., 1956a; Davies et al., 1962), and 14 (MacDiarmid and Watkin, 1972).

Data from both Herriott and Wells (1963) and Sears and Newbold (1942) suggest that for sheep, the average number of defaecations are approximately 6 per day. This estimate is supported by Hafez (1969) who reported that the average for sheep ranged from 6 to 8 daily.

The daily total ^{fresh} dung out-put by cattle has been reported as 18.2 kg (Goodall, 1951), 20.9 kg (Johnstone-Wallace and Kennedy, 1944), and 25 kg (Peterson et al., 1956a) and for sheep 1360 g (Sears and Newbold, 1942). Herriott and Wells (1963) recorded an average of 225 g of fresh dung per excretion from half-bred hoggets. This totalled $4875 \text{ kg ha}^{-1} \text{ year}^{-1}$.

The daily faecal output by a grazing animal, however, appears to be inversely related to the digestibility of the feed available. Where this varies widely during the year, dung output can similarly be expected to fluctuate, with maximum dung output occurring in winter and summer and a minimum level in periods of flush growth, e.g., spring and autumn (Bromfield, 1961).

Estimates of the area covered by each defaecation have been made predominantly in relation to cattle dung, e.g., 570 cm² (Johnstone-Wallace and Kennedy, 1944), 697 cm² (Davies et al., 1962), and 929 cm² (Peterson et al., 1956a).

Sheep dung varies considerably in physical form during the year from a usually high moisture content pad in spring to compact pellets in drier seasons or when pasture is of higher dry matter content. As a result, few attempts have been made to estimate the area covered per defaecation. Herriott and Wells (1963) concluded that dung from half-bred hoggets covered an average of 77 cm² per excretion.

2.4.1.3 Dung P content

Total P in dung is comprised of both inorganic and organic P, which may be derived either directly from the feed consumed or from endogenous P excreted by the animal.

Endogenous or body P is added to ingested feed predominantly from saliva. This may have an inorganic P content of 4 to 15 times that in blood (Preston and Pfander, 1964). Estimates from the data of Kay (1960) and Ben-Ghedalia et al. (1974) suggest that P in saliva may represent 2 to 3 times that present in ingested feed. Similarly, the results of Little (1972) indicate that in cattle the bolus total P was derived about equally from saliva and feed sources. Absorption of P largely occurs in the abomasum and ileum (Wright, 1955).

Total endogenous P in faeces tends to increase with the level of dietary P (Preston and Pfander, 1964; Braithwaite, 1975) but even at low levels of feeding may still be significant. Thus Gallup and Briggs (1950) found negative P balances were obtained (i.e., total faecal P exceeded total dietary P) when the daily P intake of lambs was less than about 0.44 g per 10 kg of live bodyweight. Bromfield and Jones (1970) also

measured negative net P balances in sheep when grazing summer pasture. The higher faecal P level was due to additions of both inorganic and organic endogenous P.

The total P content of dung is closely related to the total P intake by the animal (Bromfield and Jones, 1970) and therefore also the feed P content. For example, Floate and Torrance (1970) reported low TP levels in sheep dung of 6277 and 7374 $\mu\text{g Pg}^{-1}$ derived from Nardus and Agrostis - Festuca pastures, respectively, with TP contents of 1095 and 1345 $\mu\text{g Pg}^{-1}$ levels which would be regarded as extremely deficient for fast growing, high producing pastures (McNaught, 1970). These dung TP levels are therefore low compared with other reports of 15000 $\mu\text{g Pg}^{-1}$ derived from a high quality ryegrass-white clover pasture (Martin and Molloy, 1971) and of 20,800 $\mu\text{g Pg}^{-1}$ from a subterranean clover (Trifolium subterraneum) pasture in spring (Barrow, 1975).

Similarly, the proportion of inorganic P in faeces increases as the total P content rises (Bromfield, 1961). In agreement with this Barrow and Lambourne (1962) concluded that the level of organic P in faeces was not affected by the P content of feed and that changes in total P level occurred predominantly in the inorganic P fraction. This appears to be so even in conditions of negative P balance. Bromfield and Jones (1970) concluded that the increased faecal P level above that of dietary P was due to predominantly endogenous inorganic P supplementation rather than to any mineralization of dietary organic P. In spring-feed of higher digestibility and P content, however, up to 80% of dietary organic P was mineralized, as indicated by faecal organic P levels. The net mineralization of plant organic P to faecal inorganic P may only occur to any significant extent when pasture is in an improved or rapidly growing condition.

2.4.1.4 Release of P from dung

In the field situation the release of P from dung may occur either as a result of direct leaching of predominantly water-soluble inorganic P during rainfall or after initial microbial mineralization of organic P.

In leaching experiments using distilled water, Bromfield (1961) showed that only a proportion of the total inorganic P could be removed by severe leaching (5 successive extractions at a water:dung ratio of 80:1 shaken for 1 hour). This proportion was highest in dung of low P content, e.g., 60% of inorganic P was water soluble in dung $400 \mu\text{g g}^{-1}$ of total inorganic P but only 29% water soluble in dung containing $12,600 \mu\text{g g}^{-1}$ of total inorganic P. In a similar experiment Floate (1970a) produced contrasting results. Where the level of inorganic P soluble in 0.2N HCl was $11,600 \mu\text{g P g}^{-1}$, a total of 67% was removed by 5 water extractions, whereas 99% or more inorganic P was removed by water when this totalled only $8,430 \mu\text{g P g}^{-1}$ or less. The experimental conditions were not described and therefore these results may not be directly comparable. The results do suggest that the type of dung used in each experiment differed more than in just the proportions and levels of inorganic P. Whereas Floate (1970a) removed almost all the water-soluble P in the first extraction the P content of successive extracts was lower and the decline much less steep than with the results presented by Bromfield (1961), particularly for dung of higher P content. Neither set of results appears to support the conclusion of Barrow (1975) that faecal P is present as dicalcium phosphate. If this were so, sequential water extraction of P would show a relatively low amount of P released per extraction and a very slow decline in the P level of successive extracts, characteristic of a dissolution reaction.

The loss of inorganic P by leaching depends also on the physical form

of the dung. Bromfield and Jones (1970) reported greater P losses from crushed than intact sheep dung pellets. They also noted that losses were greater from summer samples than spring or autumn samples and considered that the difference in type of feed in each season may be a factor influencing this.

Faecal organic P is largely insoluble (Bromfield, 1961), and therefore in the short term predominantly unavailable to plants (McAuliffe et al., 1949). Floate and Torrance (1970), however, showed that incubation of faecal material with an aqueous soil extract inoculum did promote mineralization of organic P compared to incubation with distilled water alone, which encouraged only very slow P mineralization. A similar conclusion was reached by Bromfield (1961). The extent of P mineralization was significantly correlated with the organic P content of the dung and was greater in dung derived from younger plant material.

Subsequent work (Floate, 1970c) showed that mineralization of P from dung was reduced from 10% to minus 12% (i.e., 12% net immobilisation of inorganic P) by a decrease in temperature from 30^o to 5^oC and to be only slightly affected by variation in dung moisture content from 25 to 100% moisture-holding capacity (Floate, 1970d). These effects were probably related to associated changes in microbial populations (Birch, 1961; Ellis, 1974), as discussed in Section 2.4.2.3 in relation to litter decomposition. Similarly, a significant net release of inorganic P may occur only following a rapid microbial population explosion and subsequent autolysis as the substrate becomes exhausted.

2.4.2 P return via pasture litter

Dead plant material in the grazed sward consists of both standing dead matter and collapsed material or litter. Litter is considered to be the material which is out of reach of the grazing animal and generally

constitutes an older stage of standing dead matter which is at least potentially still susceptible to grazing. The difference in age will depend essentially on the amount of trampling a particular site receives. On heavy traffic areas, e.g., sheep campsites or tracks, dead plant material will quickly fall to the soil surface. The amount of plant material contributing to litter is generally inversely related to grazing pressure (Rhoades et al., 1964) but can also be affected by topography and drainage differences (Beetle, 1952).

2.4.2.1 Types of litter

Animals prefer to graze pasture high in protein and low in crude fibre (Weir and Torrell, 1959; Arnold, 1960; Blaser et al., 1960; Hafez, 1969; Frame and Hunt, 1971; Hunter, 1962). It follows therefore that the residual proportion after grazing is likely to be lower in protein and higher in crude fibre than the mean levels for the pre-grazed pasture. Not all plant material remaining after grazing fits this category, however, because some leaf material, particularly of the prostrate growing grasses and legumes, is located in positions not easily reached by stock. Such material near the base of the sward depends on the availability of adequate light for continued growth. Therefore, unless the pasture is frequently and relatively severely grazed this base level plant matter is quickly shaded and dies. Such material, however, is likely to form only a minor proportion of the annual total pasture litter under grazing, particularly if relatively unpalatable grasses or weed species occupy a significant proportion of the sward.

As discussed previously (Section 2.3) stock, especially sheep, tend to selectively graze pasture if allowed to do so. The pasture species composition will therefore affect the degree of selective grazing practiced and thus also the level of litter accumulation. In this context, it is

recognised that legumes are generally more palatable and nutritive than grasses (Lancashire and Keogh, 1966) and in mixed pasture tend to be preferred by stock.

The nutrient composition of litter material also varies during the year. Following the reproductive phase and senescence of plants in late spring and summer the pasture dead matter, and subsequently the litter material, are dominated in late summer and autumn by seeding stems. This is especially so if grazing pressure in spring has been lax and consequently the sward is grass dominant (Campbell, 1966).

Pasture fouled by dung or urine tends to be avoided by grazing stock (Sears and Newbold, 1942; Norman and Green, 1958; Marsh and Campling, 1970; MacDiarmid and Watkin, 1972). This contributes litter of a higher protein content and lower crude fibre than the average for the post-grazing condition of litter material.

2.4.2.2 Plant senescence

Once the components of pasture plants show sign of overall yellowing or browning of tissue they may be considered to be no longer in an actively growing state and therefore can be classed as part of the pasture dead matter. In reaching this condition, however, several important changes within the plant have already occurred, one of the most significant of which is the loss of some mobile nutrients by translocation. This mechanism is especially associated with the change in plant growth from a vegetative to a reproductive condition (Petrie, 1937) and the subsequent movement of nutrients from leaves and stems to the inflorescence. An N shortage, however, may induce a similar export of N from older to younger leaves, accompanied by accelerated yellowing and senescence (Williams, 1955).

Williams also concluded that P and K, and to a less extent Mg, were

similarly relatively mobile compared with S and Ca. Such nutrient movement within a plant appears to be affected by both the external nutrient supply and also the relative nutrient demand by various plant parts, including roots (Williams, 1948). Each vegetative part of a plant passes through the various conditions of accumulation, constant content, and export of mobile nutrients, especially N and P. Such mobilisation is apparently less pronounced within nutrient deficient plants.

An important influence of grazing therefore is, by repeated defoliation, to maintain the pasture plant in a vegetative condition as long as possible and to minimise the translocation of nutrients to the flowering stems. It is possible to achieve the same effect by strategic nutrient application. For example, Aspinall (1961) obtained steady and continuous tiller production in wheat by applying a low concentration of nutrients at weekly intervals. Nevertheless, once flowering does occur a large proportion of the total plant nutrient content can be located in the inflorescence (Williams, 1948) and apart from that lost in seed, this becomes potentially available for direct return to the soil via litter.

2.4.2.3 Release of P from litter

The release of nutrients from dead and decaying plant material depends on two factors. In the short term, the release depends on the proportion of nutrients that are water soluble and able to be readily removed by rainfall. The more long term and major release of nutrients is related to the microbial activity in breaking down plant cells.

The level of nutrient release by direct leaching seems to be inversely related to the conditions favouring microbial attack. This was demonstrated by Jones and Bromfield (1969) who found that although about 75% of the P in finely-ground pasture was soluble in water and the proportion tends to vary with total P content (Bromfield and Jones, 1972), the extent to which this

was actually leached depended on how much was microbially immobilized. Bromfield and Jones (1972) also showed however that during a period of from about 18 to 30 hours after initial wetting (i.e., in the non-biologically active period), a large proportion of water-soluble P could be leached from 'whole' (2.5 cm lengths) plant material using heavy simulated rainfall. They concluded that leaching of P was limited by the rate of solution and diffusion from within the intact plant.

Similarly, Halm et al. (1972) noted that the level of P in prostrate litter was decreased sharply by late summer rainfall. Their study was in ungrazed, native grassland under low rainfall conditions and these factors would have all predisposed towards a low level of microbial activity.

The processes of mineralization and immobilization of nutrients both occur during decomposition of plant material and the net effect appears related to the type of initial material. Birch (1961) interpreted this as the rate of build-up in microbial population being affected by the plant condition. He considered that young plant material promotes a microbial population explosion and a rapid exhaustion of the substrate. Subsequent death of this population releases inorganic P by "enzymatic phosphorylation processes". The microbial build-up on more mature plant material however, is smaller and the more prolonged supply of less readily-available substrate maintains a fairly uniform cycle of microbial growth and decay. Any microbial organic P mineralized in this situation is used again.

Floate (1970b) showed that N and P mineralization increased in proportion to the initial N and organic P contents of the material, respectively. It also appears that considerable N can be produced from organic materials with a quite high C:N ratio (Shaw, 1958). Earlier results by Barrow (1961) supported those of Floate (1970b) for nitrogen but Bromfield and Jones (1972) concluded that an increase in the N:P ratio resulted in increased immobilization and reduced loss of water-soluble P.

The decomposition sequence appears to be that fungi which develop on litter are attacked by bacteria (Clark and Paul, 1970). Cole et al. (1977a) have recently shown that protozoan attack of the bacterial population, releasing inorganic P, can be a further important stage in the process. Some attack of the dead plant material by fungi and bacteria appears necessary before it becomes acceptable to the majority of soil invertebrates. The final stages in decomposition of the more resistant litter components, however, probably depend on the larger soil fauna, as illustrated by Will (1968) for forest litter. Conversely, it has been suggested (Barley and Jennings, 1959) that although earthworms are very active in litter breakdown (Edwards and Heath, 1963) their major role is one of preconditioning of organic material for subsequent microbial attack. Because of the higher water-extractable P concentrations in worm casts than in the underlying soil (Sharpley and Syers, 1976), and the associated higher short-term plant availability of this P (Mansell, 1977), earthworms, where present in sufficient numbers, may also play a significant role in accelerating the rate of cycling of P.

The decomposition of material from different plant species can be associated with distinct species of arthropod fauna (Curry, 1973) and this partly explains the differences in the rate of disappearance of various plant materials. In the pasture situation, differences may not be great because as noted by Clarke and Paul (1970), the rhizosphere of grasses seem to be similar, in numbers and species, to those of a variety of non-graminaceous plants.

The seasonal variability in the decomposition rate of litter is directly related to changes in its temperature and moisture content which have most likely induced similar changes in the microbial population (Ellis, 1974). Such effects tend to be greater on bacterial than either fungal or actinomycetal numbers (Biederbeck and Campbell, 1973).

Floate (1970c) showed that the rate of C and N mineralization was sharply reduced by dropping the temperature from 30°C to 5°C. In a later study (Floate, 1970d) it was shown that between 50 and 100% moisture-holding capacity was the optimum for decomposition. Fluctuations in moisture content were found by Sørensen (1974) to increase the rate of decomposition compared with material held at a constant moisture content. Jones and Bromfield (1969) similarly found that more P was leached from samples intermittently dried than those which were kept continuously moist.

The effect of diurnally fluctuating temperature on the other hand did not increase microbial growth more than a corresponding constant mean temperature (Biederbeck and Campbell, 1973), although an increase following a period of constant temperature did increase the population. Conversely, a temperature decrease markedly reduced microbial numbers with a corresponding flush of released nitrogen.

The decomposition rate of resident litter may also be increased by the priming effect of adding a quantity of more-readily decomposable matter (Sørensen, 1974).

Any P originally in pasture litter may therefore be incorporated into the soil in one of several ways; as non-decomposed organic residues, as organic P components of fungal or bacterial tissues originating from litter, as inorganic or previously mineralized organic P, or P may reach the soil as either unchanged litter inorganic P or subsequent to mineralization from the organic form.

The high percentage of TP in litter, and the appreciable proportion in dung that is water soluble, suggest that potentially both materials may significantly contribute to immediate plant requirements. The eventual decomposition of organic residues and mineralization of other forms of P is dependent on the activity of macro and micro fauna in the soil. The higher the P content of the pasture from which both litter and dung are derived and

the higher the associated N status of the material, the more significant and rapid the contributions of both water soluble and mineralized P would appear to be.

2.5 Availability of Returned and Applied P

The usefulness to growing plants of P added to soil is of primary concern in determining not only the most efficient fertilizer practice to employ in terms of type, rate, and frequency, but also to appreciate the significance of supplementary contributions from plant material and animal dung. The level of these contributions are affected by grazing management and may therefore be manipulated to complement the topdressing policy.

The major and obvious difference between both pasture litter and dung, compared with inorganic fertilizers, is the organic component of the biological materials. This has implications to the relative contributions of each source of P to the soil organic P fraction and conversely the usefulness of each as a short-term source of plant-available P. As discussed in Section 2.4.3.1, P from organic residues may reach the soil in either organic or inorganic form, the proportion depending largely on the original type of material and the prevailing environmental conditions. Organic P from litter and dung may be considered, at least in the short term, to contribute only to soil organic P and therefore not to constitute any significant immediately available form of P. The validity of this assumption over a longer period will depend largely on the extent to which active soil organic matter accumulation is still occurring. This will itself be affected by such soil properties as pH, C/N ratio, and soil P status (Walker, 1965). At a steady-state soil organic P level, the rate of organic P mineralization must by definition, be similar to that of organic P addition or inorganic P

immobilization. Seasonal changes in some organic P fractions may also occur. Halm et al., (1972) showed that the NaHCO_3 -soluble organic P level varied during the year, increasing during the period of maximum growth and highest microbial activity whereas the NaHCO_3 inorganic P levels remained constant.

Inorganic P entering the soil solution may be used in several ways. It may be taken up by plant roots or by microbial decomposers. Cole et al. (1977) consider the latter to be about 20 times more efficient at absorbing inorganic P than plant roots and therefore are particularly competitive at low soil P levels. Alternatively P may be sorbed by soil components with a range of bonding energies to become either essentially non-exchangeable or rapidly exchangeable with P in solution.

2.5.1 P from organic residues

Few assessments have been made of the availability to growing plants of P from dead plant material. Mansell (1977) has recently shown that over a 4-week period ^{32}P -labelled pasture litter contributed to plant P uptake and that this was accelerated if the litter was first ingested and subsequently excreted as surface casts by earthworms. Any difference between litter and derived cast material in terms of long term P availability was not determined.

Assessments have been made of the total effect of returning pasture clippings to mown plots compared with not returning them (Lynch, 1947), as measured by subsequent pasture production and composition. The return of clippings technique has also been compared with various grazing, or dung and urine return, treatments (Elliott and Lynch, 1958). Observed and measured sward deterioration as a result of not returning clippings was largely attributed to depletion of soil N and K more than to depletion of P; a conclusion also reached by Wolton (1963).

The usefulness of dung as a source of plant available nutrients has been studied more widely. Some measurements have been a combined assessment of both dung and urine application (Sears, 1944, 1950; Metson and Hurst, 1953; Sears and Thurston, 1953), with the effect being interpreted by comparison with non-return areas. Other trials have included treatments where the effect of dung alone was assessed (Sears and Newbold, 1942; Sears et al., 1948; Watkin, 1954, 1957; Melville and Sears, 1953; Wolten, 1955; Wheeler, 1958). In some experiments simulated dung and urine treatments have been used, (McNeur, 1953; Holliday and Wilman, 1962; Wolten et al., 1970).

Dung, or simulated dung treatments have been found to have no immediate beneficial effects on pasture growth but these often appear after a period of time. Wolten (1955) recorded pasture growth increases from dung about a year after the start of the trial. During (1972) found that over four years the uptake of P from cattle dung was just as efficient as that from superphosphate. Similarly in the third and fourth year of a field trial Sears et al. (1948) measured an 18% higher pasture production on 'dung only' plots than on those receiving neither dung or urine. By comparison, 'urine only' plots and 'full return' (dung plus urine) plots produced 15 and 33%, respectively, more than the control. These results suggest that there was no interaction between nutrients in dung and urine when applied to pasture simultaneously; the increased dry matter produced from full return being an additive effect only. Watkin (1957), however, reported a positive interaction between dung and urine in increasing pasture growth. Because both dung and urine contain appreciable levels of K it is likely that this interaction was principally between P in dung and N in urine. This is supported by the results of Holliday and Wilman (1962) who found a positive interaction between N and dried dung plus nitrochalk in

increasing pasture growth. A similar interaction occurred between clover and these "animal residues" after a year of the trial. Again this is most likely an effect of increased soil N. The build-up of clover in "dung only" pasture plots was earlier noted by Sears and Newbold (1942).

Wheeler (1958) similarly emphasized the need for high associated levels of nitrogen before dung produced a significant pasture response. By contrast Bromfield and Simpson (1974) found that although high grazing pressure increased N availability in the surface soil, P or S availability was not affected.

Gunary (1968) concluded that although P in sheep dung may be readily available its effectiveness depends on the degree of dung/root contact. Therefore, dung must be incorporated into the soil to obtain the greatest benefit from faecal P. In the field the presence of dung itself may be a factor stimulating soil fauna which will encourage dung breakdown and incorporation into the underlying soil. Watkin (1954) noted a significant build-up in the population and activity of earthworms in dung only, and dung plus urine treatments, also receiving high rates of N. By comparison, earthworm numbers were low on the respective urine only treatments.

Dung/root contact may also be greatly improved when dung is in a very fluid state. This could have been a major factor in the results of Hanley and Murphy (1976) who found slurries of cow and pig dung to compare favourably with other sources of N, P, and K, particularly over periods greater than two months after application.

Because inorganic P is relatively immobile in most soils the improvement of root/P contact, or the increase of available P status at depth, both of which may be accomplished by earthworms, may be achieved largely by the more labile organic P fractions from litter or dung which have greater mobility. This may explain why Elliott (1972) reported significant P losses

from lysimeters receiving dung, but not from those receiving superphosphate. Mineralization of organic P at depth may in some seasons provide a useful source of available soil P.

2.5.2 P from fertilizer

The evaluation of P as a fertilizer element has been more extensive than that of any other plant nutrient. The need for clear definition of the long-term availability to pasture of fertilizer P is becoming of increasing interest and concern in New Zealand. This stems not only from the increasing cost and diminishing sources of supply of phosphate rock but also because most of the potential farmland is now in pasture and requires more of a maintenance than a development top-dressing. During (1972) has reviewed the bulk of New Zealand field work conducted primarily by the Department of Agriculture and subsequently the Ministry of Agriculture and Fisheries. The topic can only very briefly be covered in this review.

Phosphate fertilizers are almost entirely solid materials applied to the soil for plant root absorption. Some foliar sprays have been used but these appear to offer limited scope for correcting P deficiency because P intake via leaves is slow compared with that of root uptake (Bouma, 1968). Karlovsky (1975) concluded that although liquid P fertilizers may have a similar effect they were much more costly per unit of P than solid fertilizers in New Zealand.

An example of the range of materials that can be used as P fertilizers were those evaluated by van der Elst and Karlovsky (1953). This trial showed that over four years all 10 materials used, and compared on a unit P weight basis, stimulated pasture growth to a similar extent, but that yield response was not directly related to fertilizer P content. e.g., serpentine super (6.5% P) and double super (21.4% P) gave the same response (99% of that produced by superphosphate with 9.2% P). The greatest pasture production

was from thermophos (calcium-magnesium phosphate at 7.8% P) and basic slag (7.4% P) treatments. Great care is required in interpreting P responses from such 'compound' fertilizers because of the nutrient interactions that can occur. Walker et al (1955) noted such interactions in evaluating S and Mo with P fertilizers. During et al. (1960) reported both positive and negative interactions between various nutrients. Similarly, Cullen (1958) found that lime added with North African and Nauru ground rock phosphate depressed growth whereas yields from superphosphate, serpentine superphosphate, and thermophos treatments were enhanced with lime.

A characteristic sigmoidal response curve is derived by measuring pasture dry matter production at increasing levels of P topdressing. The initial, increasing rate of plant P uptake, as the applied P level increases is explained in terms of the progressive saturation of P sorption sites and an increasing proportion of applied P remaining in solution of which the plants take full advantage. This same process continues throughout the range of further P application. At the higher levels of topdressing, however, the ability of faster growing plants to fully use available P appears to become limited by such other factors as relatively inefficient root exploration and the availability of other nutrients. Consequently, the marginal increase in dry matter growth per unit addition of P gradually declines and increasing proportions of applied P is subsequently not used. A compromise must therefore be reached between that level of production near the maximum, and a lower level which may be largely set by economic factors.

The level of annually applied P required to maintain a certain level of pasture growth must, over a long period, represent the sum of both "above-ground" and "below-ground" losses. Karlovsky (1975) concluded that at a high level of pasture production and utilization by grazing stock these losses occur predominantly "above ground" and therefore can be minimized by prudent management. Conversely, estimates of "apparent" P recovery from

the soil, by comparing total P uptake from both topdressed and untopdressed plots over a long period have been as low as 15 to 30% (Russell, 1954) and 27 to 50% (During, 1972).

Because most of the P taken up by plants in grazed pasture is returned to the soil as dung, a proper evaluation of the efficiency of a P fertilizer should also incorporate the subsequent availability of P from dung. This assessment can only be made after a long period of topdressing by which time dung has been returned uniformly to the whole grazing area. At this time, annual plant P uptake can be related to the total P return to the soil in fertilizer, litter, and dung because soil P levels will remain relatively constant.

Karlovsy (1961, 1962, 1966) adopted this approach but expressed plant uptake in this context as a "percent P utilization". This interpretation gives a false impression of the efficiency of P recovery by pasture because plant uptake in one year is related only to P input in the same year without recognising the previous P inputs that have brought the soil P status to the existing level. In the control situation, where no topdressing was applied, P return via dung and litter would, because of some above ground losses, be less than that of plant uptake. Consequently, the derived P utilization efficiency would in this case exceed 100% as mobilization of P from soil reserves occurred. Similarly, low levels of P topdressing are associated with high P utilization percentages and lower utilization efficiencies are derived from higher topdressing rates to the same soil. While the relative order of these estimates are correct, they are inflated by the influence of the total available soil P level.

A more correct definition of the efficiency of utilization of applied P may be obtained by subtracting the control level of plant P uptake from the treatment P uptake level before relating it to total P inputs for any year. Such modification would derive a much lower and more compact range

of P utilization efficiencies for any given range of P topdressing rates than by the Karlovsky method and would be more realistic, especially at low levels of topdressing. Such levels of efficiency would also relate more closely to laboratory experimental results. For example Peaslee and Balleaux (1977) in sequential desorption experiments (using 10^{-3} N CaCl_2 as the extractant solution), covering a period of 88 hours, were able to recover only 15 to 30% of applied P.

The estimation of P utilization efficiency is to some extent of academic interest only because the aspect of major concern is the level of pasture growth that can be maintained on a particular soil by a certain fertilizer input. It is important, however, to appreciate the true role of added, compared with native, soil P in its contribution to total pasture growth. As suggested by During (1972), the data from long-term P response trials perhaps may best be used to derive an estimate of annual "below ground" losses of P by immobilization and leaching (i.e., total applied P per year less plant P uptake) over a range of pasture production levels.

2.6 Above Ground P Losses

The "above ground" components of the P cycle in grazed pasture potentially offer the greatest opportunity for manipulation and therefore largely determine the efficiency of the P cycle in operation. Losses of P may be sufficiently large as to effectively disrupt the cycle or the components so controlled that net losses are small or non-existent. The three main P loss pathways to consider are in animal products, by animal transfer, and in surface runoff water.

2.6.1 P losses in animal products

On most hill-country properties the animals sold are store wether lambs, surplus 2-tooth ewes, and cull mature ewes, and some weaner and cull-breeding cows. Fattening of young stock may occur where suitable areas of flatter land are available.

The bones and teeth of animals contain about 80% of body P, with the balance present in organic combinations, e.g., phosphoprotein, nucleoprotein, phospholipids, phosphocreatin, hexose phosphates, and others (Maynard, 1947). Bones and teeth contain between about 5 and 10% P (mean 8.5% P., Agricultural Research Council, 1965) and body tissues 0.15 to 0.20% P.

The annual P losses in animal products from a store sheep farm carrying no cattle (for simplicity of estimation) may be calculated as follows:

A 27 kg carcass weight Romney ewe contains about 9.3% bone, 48.4% muscle and 39.8% fat (McMeekan, 1959). This represents about 210 g P in bone and 40 g P in other tissues. If the average wool production from ewes and wethers was 4.5 kg, then this represents a further 9 g P per animal. Assuming a stocking level of 11 stock units ha^{-1} with a culling rate of 20%, this amounts to a net loss of about 550 g P ha^{-1} per year. If lambing is 80% from ewes of the above body weight (Hight and Wright, 1972), wether lambs are sold as stores at 34 kg live-weight and surplus ewe lambs above flock replacement requirements are sold as 2-tooths at 45 kg live-weight, then this represents a further loss in animal products of about 1220 g P ha^{-1} , i.e., a total annual loss of 1770 g P ha^{-1} . The estimated P loss from a cattle only system is similar.

If it is assumed that 550 kg of pasture containing 0.35% P is necessary to support 1 stock unit then the annual P loss in animal products represents about 8.4% of pasture P uptake. At an 80% level of pasture utilization by

stock this represents 10.4% of animal P intake.

2.6.2 P losses by animal transfer

The non-uniform return of animal dung and urine to grazed pasture may, over long periods, induce marked changes in soil nutrient status. This can occur within paddocks, as measured by Hilder (1966) with Merino ewes, or between paddocks as on some dairy farms with established "day" and "night" paddocks. The greater proportion of dung and urine return by cows at night, compared with that during the day (Hancock and McArthur, 1951), results in a gradual transfer of nutrients to paddocks predominantly used for night grazing (Sears, 1956) with associated effects on pasture production and species composition. Such effects can be corrected by more flexible stock management.

Within-paddock differentiation in pasture composition and soil P status is generally not marked on flat-land but is much more apparent in hill paddocks. Some of this variability can be attributed to soil and microclimatic differences but, as demonstrated by Gillingham and During (1973), most can be related to markedly lower returns of N, P, and K in dung and urine than the amounts taken-up by pasture. Net transfer losses of P were proportionately greater on moderately-steep slopes (i.e., 38% of pasture P uptake) than on flatter sites adjacent to camp areas (i.e., 4.6% of pasture P uptake). No equivalent data are available for P transfer losses on flat land although some estimates have been made (Karlovsky, 1975).

2.6.3 P losses in surface runoff water

Phosphorus losses in surface runoff are predominantly associated with sediments i.e., particulate forms which include both 'native' P and 'fertilizer' P (Burwell et al., 1975). The latter may comprise both fertilizer particles

and fertilizer P sorbed onto soil particles. Additional losses may occur as dissolved inorganic P. Under topdressed conditions therefore the contribution from fertilizer to surface runoff losses may be expected to increase markedly (Sharpley, 1977). In developed pasture, gullies and stream channels contribute the majority of sediment (Schouten, 1976) which may itself sorb appreciable amounts of inorganic P from solution (Sharpley, 1977).

The actual P loss from pasture will depend on factors affecting both the amount of surface runoff and the P status of the surface soil. In hill pastures these will depend on the grazing management and topdressing policies being applied. Significant earthworm casting activity during winter (Sharpley and Syers, 1976) may comprise an important additional source of particulate P to surface runoff.

On most hill areas widespread surface runoff does not generally occur over long distances and may only make any contribution to streams when derived from slopes in close proximity (Betson, 1964; Ragan, 1967; Dunne and Black, 1970). Movement of soil particulates over short distances from steep slopes to adjacent stock tracks could involve appreciable depletion of surface soil P under suitable conditions. Of more significance may be the transport of whole litter and dung material from slopes to tracks, thus removing the source of potentially plant available P. Conversely, some washing of dung, litter, or soil may occur from campsites or tracks to lower slopes. The significance of these effects in steep, grazed pastures is unknown. It has been suggested that surface runoff from more gentle slopes at times contains appreciable levels of P derived from animal dung (McCarty, 1967; Holt et al., 1970) and pasture litter (Cowan and Lee, 1971; Taylor et al., 1971).

Both vegetation type and maturity affect the level of P loss (White and Williamson, 1973). In addition loss of P from plant material can be accelerated by alternate freeze and thaw conditions (Holt et al. 1970).

Consequently, microclimatic differences between north and south aspects could, in colder regions, be associated with differences in P loss rates where surface runoff also occurs.

2.7 General Conclusions

Study of the movement of P from soil to plant and its return to the soil by various pathways enables a measure to be obtained of the relative significance of each component in the overall cycle. Total amounts of the differing forms of P present in various compartments of a P cycle can be determined relatively easily. The definition of transfer rates between compartments, however, is of greater importance but more difficult to obtain. For this reason most studies have been made on systems at an equilibrium where component levels are stable and therefore rates of P movement can be more readily determined. Examples of such systems are ungrazed rangelands as studied by Halm et al (1972) and modelled by Cole et al. (1977).

Research on soil P has been occupied predominantly with an evaluation of the forms of soil P and their relationship to plant uptake. Such studies have generally involved the measurement of P in two or more compartments only, but usually divorced from other aspects of a P cycle. Although considerable progress has been achieved with respect to defining P sorption characteristics of soil constituents the process of P desorption is less well understood. Similarly, the many methods of defining plant available P, either with or without the aid of isotopes, all appear to have some limitations in their interpretation and application. In most instances a definition attempts to relate a single instantaneous measurement of soil P to equivalent plant uptake which may extend over one or more years. A compound measurement incorporating several factors (e.g., buffer capacity and pH) may be necessary

to satisfactorily define total plant available P over a range of soil types and levels of P. Conversely, a more frequently used 'immediately available' P test may be preferable.

Uptake of P by plants can readily be determined. More difficult is the assessment under field conditions of P return rates from plant litter. The presence of the grazing animal obviously introduces factors of animal-product loss and transfer that may make an equilibrium slow or impossible to achieve, particularly where large numbers of animals are involved. An examination of a P cycle under grazing conditions is therefore comparatively difficult. While isolated studies have been made on the release and availability of P from dung, there has been little attempt to specifically evaluate the effects of pasture grazing utilization and excretal return on the efficiency of P cycling. Even an approximate assessment of the above ground components is desirable in order to determine the relative importance of the soil factors. Few attempts have yet been made to do this. A recent paper by Blair et al. (1977) is one of the first.

SECTION 3

PHOSPHORUS UPTAKE AND RETURN
IN GRAZED, STEEP, HILL PASTURES

3.1 Introduction

The fertilizer requirements of a pasture may be determined by measuring soil nutrient levels and relating them to established topdressing response curves. In the absence of any such response curves an alternative, but more time-consuming, method is to measure losses occurring in the nutrient cycle and to compensate for these by fertilizer addition. Because of difficulties associated with such measurements there has been little work in North Island hill country to establish pasture growth responses (During, 1972), especially to P which is the most widespread fertilizer element applied. It is possible that because of topographic complexity and associated soil variability that measurement of losses from the P cycle in such situations may provide information of more reliability and more widespread application.

Studies of the P cycle in native pastures (e.g., Halm et al., 1972; Cole et al., 1977) have provided useful insight into the amounts of P in various soil "compartments" and the rates of P movement between these compartments, especially as affected by the equilibrium between organic and inorganic forms of P. Native grassland soils, however, are generally of relatively low P status and the pastures low also in nitrogen-fixing species. Consequently, these systems are of limited value in interpreting P cycling under a higher producing, intensively grazed pasture such as is found in many parts of New Zealand.

The major effects of the grazing animal in the P cycle are to reduce the amount of litter that would otherwise form and to convert plant P into faecal P, which is redistributed in scattered clumps at high equivalent P

application rates. The assessment of the P cycle under grazed conditions is therefore appreciably more difficult than in undisturbed native grasslands. In a recent paper, Blair et al. (1977) described the P cycle in a grazed flat land pasture and used it to examine 'sensitive areas' within the cycle. This appears to be the first P cycle model incorporating grazing effects which has also been based on, and validated by, field data. Theoretical P and N cycles relating to grazed British hill pastures were earlier developed by Floate (1970a) from the results of laboratory experiments only.

The overall efficiency of a P cycle may be described by the level of topdressing required to maintain pasture production and soil P status, i.e., to compensate for P losses. Such losses may occur in the soil by immobilization or leaching, by disproportionately low dung return ("transfer") or by complete removal from the grazing area as animal products. The relative importance of such "above ground" losses will vary with stock type, management, and topography. Using this approach, Karlovsky (1961) derived estimates of apparent P utilization efficiency for superphosphate applied to flat land. The unknown variable corrections required for P transfer from various parts of a hill paddock restrict application of such a technique to less complex topography.

While measurements of differences in pasture production (Suckling, 1959) and soil nutrient status (Saunders and Auld, 1969) attributable to fertility transfer have been made, only one study (Gillingham and During, 1973) has attempted to measure annual rates of transfer occurring in grazed hill pastures. In that study net P, K, and N balances were derived for each of several strata within a paddock, allowing for some removal in animal products. While the various paddock strata tended to be topographically different, no attempt was made to relate net losses or gains of nutrients to

either slope or aspect. The assessment of any relationship between "above ground" P losses and the slope and aspect of the soil surface would appear to be an initial requirement for better appreciating top-dressing needs of hill pastures. The above study area was a paddock of predominantly rolling to moderately-steep topography. In contrast, no measurements of P cycling have been made in steep, tracked hill pastures typical of a large proportion of New Zealand North Island hill country.

The trial described in this Section was conducted to provide information on the annual "above ground" net P balance on different slopes in two grazed, steep hill pastures. The net P balances are discussed in relation to measured soil P levels, to pasture species composition, and to grazing management as they affect the relative importance of animal dung and pasture litter P return and associated topdressing requirements.

3.2 Materials and Methods

3.2.1 Trial site

The trial area was at Whatawhata Hill Country Research Station, latitude 37° 48'S, altitude 220m, 25 km west of Hamilton in the North Island of New Zealand. The trial site consisted of two steep hill paddocks, one on a north- (Plate 3.1) and one on a south- (Plate 3.2) facing aspect. Details of paddock area and slope composition are shown in Table 3.1. The method of determining slope composition of each paddock is described in Appendix II.

Both paddocks had been in pasture for many years although gully bottoms on the south-facing aspect still contained some native ferns, shrubs, and trees. Pasture on ridge crests and campsites was dominated by ryegrass (Lolium perenne, L.) and annual meadow grass (Poa annua, Poir),



Plate 3.1 Study area paddock with a north-facing aspect.



Plate 3.2 Study area paddock with a south-facing aspect.

whereas the slopes on both aspects contained a similarly large number of species to those reported by Radcliffe et al. (1968) for a nearby site.

The steepest slopes were dissected horizontally by well-defined stock tracks which contained similar pasture to that on the campsites. The transverse slope of tracks did not exceed 30° and therefore all were grouped in the 25° slope category (Table 3.1). Apart from those tracks judged as campsites, the remainder comprised 11.2% and 19.6% of the total area on north and south aspects, respectively.

The soil on both aspects is predominantly a Waingaro steepland soil (Bruce, 1976), a northern yellow-brown earth derived from argillaceous greywacke. Some volcanic ash is present on ridge crests which, therefore, are more free draining and have a slightly higher phosphate retention capacity than the soil on the slopes.

The area has been annually topdressed with approximately 315 kg ha^{-1} of superphosphate which at times has included both Mo and K. A further routine maintenance application of 250 kg ha^{-1} of superphosphate was made on February 10, 1976. A total of 5000 kg ha^{-1} of lime has also been applied within the previous 5 years. The trial site is part of a larger trial area that was earlier used to assess limitations to hill-pasture production. Part of the above heavier than maintenance topdressing history was intended to ensure that plant nutrients were not limiting on this site. It was for this reason that the site was considered desirable for the P cycling study. Although available soil P levels were higher than on most hill country, pasture production would then be limited only by climatic and management effects. If in such a situation therefore grazing achieved a high level of pasture utilization then the grazing animal would have its greatest influence on the above-ground components of the P cycle.

Table 3.1 Paddock slope composition
(% of total area per stratum)

Stratum	North aspect			South aspect		
	Proportion of total area	Mean slope	Area comprising tracks	Proportion of total area	Mean slope	Area comprising tracks
	(%)	(°)	(%)	(%)	(°)	(%)
Campsites	20.1	12	-	12.2	15	-
25° slopes*	55.7	24	11.2	45.5	25	19.6
45° slopes**	24.2	43	-	42.3	44	-

* Includes all readings on slopes up to 30°, excluding campsites.

** Includes all readings from 35° and steeper slopes.

3.2.2 Grazing Management

The trial commenced on September 1, 1975 and concluded on August 31, 1976, spanning four seasons; spring (September 1 to November 30), summer (December 1 to February 29), autumn (March 1 to May 31) and winter (June 1 to August 31).

The pasture was grazed at a high utilization level by Romney wether hoggets so that no rank pasture accumulated in any areas of the paddock. This generally involved a grazing period of 1 to 3 weeks with a spelling interval of 2 to 6 weeks, according to rate of pasture growth. Details of grazing management are shown in Appendix III.

3.2.3 Sampling procedure

Within each paddock three types of topographic strata were sampled:

- A - sheep camp or ridge sites and also including some track sites as noted in Appendix II
- B - 25^o slope sites
- C - 45^o slope sites

On each type of strata, P uptake in pasture and P return in pasture litter and sheep faeces were measured. In each paddock, five blocks were selected within which all measurements were made.

3.2.4 Phosphorus uptake

This was derived from measurement of the total pasture dry matter production and the P concentration at each harvest.

3.2.4.1 Pasture dry matter production

This was measured by the trim technique (Lynch and Mountier, 1954). While not exactly simulating the grazing pattern, which sometimes

contained long-grazing periods, this method was considered able to provide a reasonable, relative measure of pasture production from all sites.

Within each block on each type of strata (A, B, and C) were located five small (0.2 m^2) plots which were randomly selected as successive sites for measurement of pasture growth rate. Three plots were therefore used twice and the other two once only. The cutting interval varied from about 4 weeks in spring at the time of most rapid growth to almost 12 weeks in winter. Total dry weight of pasture from all cuts was measured after drying at 60°C for 24 hours. Two subsamples of pasture were taken from the second cut in spring, summer, and autumn and the single winter cut. The first subsample was dissected into grasses, legumes, weeds, and dead matter and measured on a dry-weight basis. The second subsample in each case was freeze dried and finely ground using a Glen Creston mill prior to chemical analysis.

3.2.4.2 Assessment of P limitation to pasture dry matter production

Both paddocks in the trial area had a history of generous topdressing, particularly in recent years. It is unlikely that pasture growth during the trial was limited by P deficiency. For satisfactory interpretation of slope and aspect effects, however, it was necessary to determine if any such limitations existed. For the purposes of this study it was sufficient to determine if a pasture dry matter response to additional fertilizer could be obtained, rather than attempt to define any P response curve.

Because of the very high soil P levels already present in campsites and therefore the extreme unlikelihood of obtaining a response to topdressing on these sites, the trial was limited to 25° and 45° slopes only. Superphosphate was applied at two rates; 0 and 1250 kg ha^{-1} . Treatments were

replicated nine times. Five of these replicates were located within the five blocks in each paddock selected for other measurements. Pasture dry matter production plots on 25° and 45° slopes constituted the control or zero topdressing treatments. Five additional plots in each stratum were selected and topdressed. In practice, plots were all chosen before randomly allocating those to be topdressed. Four additional blocks were chosen within each paddock and 25° and 45° plots similarly selected.

Fertilizer was applied to a 0.6 m² plot and pasture growth rate measured from a 0.2 m² central area, as described in Section 3.2.4.1. Dry matter oven-dry weight only was recorded.

3.2.4.3 Pasture P concentration

Total phosphorus (TP) was determined using the ternary acid method described by Jackson (1958) except that H₂SO₄ and HClO₄ only were used in the same proportions. Following neutralization of the extract, inorganic P was determined colorimetrically using the method of Murphy and Riley (1962), absorbance being measured at 712nm using a Unicam SP1800B Spectrophotometer. This method was used for all inorganic P determinations.

Water-soluble P was extracted from a 40:1 ratio of water and plant material by shaking end-over-end for 2 hours at 23°C. After centrifuging at 1,000 rev. min⁻¹ for 3 min at 23°C using a Sorvall RC-2B high-speed, refrigerated centrifuge, the samples were Millipore (<0.45 µm) filtered. The water-soluble inorganic P (DIP) was then measured, as was the total water-soluble P (TDP) following acid persulphate digestion and autoclaving at 15 p.s.i. for 45 min (Environmental Protection Agency, 1971). Water-soluble organic P (DOP) was derived as the difference between TDP and DIP.

3.2.5 Phosphorus return

This was obtained using the dry weight of dung and litter that had

accumulated on fixed plots between samplings and the P content of "fresh" dung and dead pasture collected midway (as in Spring, Summer, and Autumn) or at the end (as in Winter) of each season. The P content of urine is negligible (Sears and Newbold, 1942; Barrow and Lambourne, 1962) and was disregarded as a component of P return.

3.2.5.1 Total dung dry weight

On each type of strata within each block, three 0.20-m² plots were randomly selected as fixed sites for collection of the dung deposited during grazing. After the first sampling these were increased to seven plots on camp sites and six on 25° and 45° sites in order to obtain a more reliable sample.

Plot boundaries were located by a wooden frame placed around metal pegs in each corner of each fixed plot. For ease of collection the frame was divided by cord into 12 subplots which were each cleared (Plate 3.3).

Dung was collected at the end of each grazing period, except in spring when grazing was more prolonged than in other seasons. During spring, dung was collected at two-week intervals if the grazing period exceeded this. Dung was weighed after drying overnight at 105°C.

3.2.5.2 Field trial dung for P analysis

The dung collected from plots open to grazing was unsuitable for the various P analyses for two main reasons. First, any dung on the pasture could be trampled and contaminated with soil; this was particularly likely on A sites. Second, unless collected immediately after deposition the dung would be liable to incur losses of water-soluble P during any subsequent rainfall. Consequently, "fresh" dung was collected from harnessed animals (three per paddock) during early and late grazing periods in each season. The animals were randomly selected, penned in an enclosure

within each paddock, harnessed and released following collection of the fresh sample some 6 hours later. This collection usually occurred on one of the last 3 days of the selected grazing.

3.2.5.3 Dung P concentration

No information was available as to the effect of sample pretreatment on the level of various P fractions within sheep faeces. Consequently, prior to the field trial a comparison of sample preparation methods was made. This was conducted in autumn on samples of freshly-voided dung collected from sheep grazing two very different types of pasture. One sample was collected from an "improved" well-grazed and regularly-topdressed pasture and the other from a previously-farmed area that was in a rank, laxly grazed "unimproved", condition, with clumps of cocksfoot (Dactylis glomerata), Yorkshire Fog (Holcus lanatus) and browntop (Agrostis tenuis) predominating. Dung was analyzed in a fresh, freeze-dried, frozen, and oven-dried condition both as whole pellets and as crushed and mixed material. In addition, the freeze-dried and oven-dried samples were passed through a 2-mm mesh.

Measurements were made of DIP and TDP, as for the pasture samples and DOP derived as the difference both for single and sequential extraction experiments.

Total P (TP) and total inorganic P (TIP) were measured by the method of Walker and Adams (1958) and compared with the Anderson-Mehta method (Anderson, 1960).

From the results of this comparison the following method of sample preparation and analysis was selected for use in the field trial. Dung was freeze-dried, crushed, and sieved (< 2 mm) prior to analysis. Total P and TIP were determined by the method of Walker and Adams (1958). DIP and TDP were measured as described above.

3.2.5.4 Total litter dry weight

On each type of strata two of the fixed plots used for dung collection were also selected for litter collection at the end of each grazing period. The litter collection plot was 0.13 m² in area and was defined by eight of the sub-plots within the same wooden frame used for dung collection (Plate 3.3).

Litter was defined as dead plant material present in the pasture below grazing level at the end of the grazing. This included both loose and attached material. It also included any whole plants that had been uprooted during grazing and then rejected. Litter was washed on a 2-mm sieve, dried at 60°C, and dissected into leaf and root material which were each weighed.

3.2.5.5 Litter P concentration

The litter collected was unsuitable for determining P concentration because such analysis would not account for any P lost while on the plot as standing dead material. Consequently a technique was developed to produce "fresh" litter.

This was obtained by shading separate areas of pasture and collecting the shaded material when dead. The shading commenced at or before the beginning of grazing and was provided by a black plastic sheet over a metal frame with side ventilation to allow drying and to prevent decay of the dead pasture. The cover also prevented any leaching of P from the "litter" by rainfall. Litter P concentration was measured at each mid season on grass material only by the same procedure used for pasture analysis. Grass only was used because this was found during the trial to comprise virtually all of the pasture litter collected.



Plate 3.3 Dung and litter collection plot. Dung was collected from the complete (0.2 m^2) plot and litter was collected from only the 8 subplots occupying the central and left side longitudinal thirds.

3.2.6 Soil phosphorus

Soil P determinations described below provided a measure of immediately plant-available P (DIP), labile organic P (TDP less DIP); "available" soil P (Olsen P) and total P (TP) status.

Soil P status was monitored by sampling at the middle and end of each season. Two core samples (1.9-cm diameter) were collected adjacent to each of the five pasture measurement plots per strata in each block and bulked to form one sample. The first sampling on October 1, 1975 and the final sampling on September 1, 1976 were at 0-3, 3-7, 7-15, 15-30, and 30-45 cm depths. All other samplings were to 15 cm only.

Following collection, samples were frozen until they could be freeze dried then ground and sieved (< 2 mm). Total P, TDP, and DIP were measured as for dung samples. Soil samples collected at each mid season were also analyzed for P by a modified Olsen test (Olsen et al., 1954) in which P release to $0.5M$ $NaHCO_3$ (pH 8.5) at a solution:soil volume ratio of 50:1 during 30 min was determined. Results as $\mu gP\ ml^{-1}$ soil were converted to $\mu gP\ g^{-1}$ by reference to the relevant soil bulk density of each sample. Soil organic matter content (% by weight) was derived from the sample weight difference before and after ignition and expressed as a % of oven-dried soil weight.

3.3 Results and Discussion

3.3.1 Phosphorus uptake

3.3.1.1 Pasture dry matter production

Total pasture production for the year was high on the campsites on both north and south aspects but decreased sharply with increase in surface slope (Table 3.2).

Table 3.2 Seasonal and annual pasture production
(kgDM ha⁻¹) from each stratum

Season	North aspect			South aspect		
	Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
Spring	4975	3880	2200	4990	2590	1805
S.E.*	215	212	118	385	172	119
Summer	2600	2445	1460	4195	2640	1440
S.E.	236	252	112	41	198	195
Autumn	1785	1460	1035	1915	1200	1060
S.E.	173	182	164	181	125	111
Winter	1780	810	670	1290	680	405
S.E.	129	69	114	109	70	63
Total	11140	8595	5365	12390	7110	4710
S.E.	753	715	508	716	565	488

* Standard Error of the estimate.

Pasture growth on the south aspect campsites was greater ($P \leq 0.01$) than on the north aspect only in summer (i.e., 4195 compared to 2600 kg DM ha⁻¹) but the opposite occurred in winter ($P \leq 0.05$), i.e., 1290 compared to 1780 kg DM ha⁻¹. Consequently, total annual production did not differ between the two sites being 12,390 compared to 11,140 kg DM ha⁻¹ on the south and north aspect campsites, respectively.

Although seasonal pasture production from the 25° slopes was consistently higher from the north than from the south aspect, the difference was significant only in spring ($P \leq 0.01$), i.e., 3880 compared to 2590 kg DM ha⁻¹ and did not result in better annual growth.

On the 45° slopes the difference in pasture dry matter production between aspects was significant ($P \leq 0.10$) in both winter and spring.

The above indication that pasture growth on north-facing slopes tends to be greater than on south-facing slopes supports results by Suckling (1975) in the southern North Island and results from elsewhere at Whatawhata (Gillingham, 1973). This result is in contrast to that of Radcliffe et al. (1976) for South Island hill country, where production from south-facing slopes was higher, and also to those by Burnham et al. (1970) for Scottish hill country where no effect of aspect was measured over a range in altitude.

The marked seasonal nature of the pasture growth pattern (spring growth comprised an average of 43.6% of the total on the north aspect and 38.3% of that on the south aspect) illustrates the problem of pasture control faced by the hill-country farmer, especially those with limited ability to adjust stock numbers during the year.

3.3.1.2 Assessment of P limitation to pasture growth

The trial conducted to determine if pasture growth on 25° and 45° slopes was limited by P deficiency at any time of the year gave a pasture dry matter response on only one occasion. The additional growth

occurred on the south aspect 25° slopes in autumn (Table 3.3). No response was measured on 45° slopes. Similarly, the additional fertilizer applied did not significantly affect total annual production on any site.

It is of interest that on 25° slopes the only topdressed plots to produce less than the untodressed were on the south aspect in summer, i.e., measured pasture growth was highest from all other topdressed 25° slope plots but significantly so at only one time. Similarly, production from topdressed plots on 45° slopes was slightly higher in five of the eight measurements made. It is perhaps possible that the real pasture growth response to the additional 1250 kg ha⁻¹ of superphosphate was more widespread than statistically detected. This would be surprising however, in relation to the liberal past topdressing and higher than average soil P levels.

3.3.1.3 Pasture species composition

Campsites were markedly different in pasture species composition from the remainder of each paddock (Table 3.4). They were characteristically ryegrass dominant, especially in winter and spring, with very few legumes. In late autumn, annual meadow grass became established and during late winter and spring made a noticeable contribution to pasture growth on campsites. In summer and autumn, paspalum (Paspalum dilatatum, Poir) partly replaced other grasses. The south aspect maintained a more stable pasture composition than the north throughout the year, particularly in relation to legume content. White clover (Trifolium repens) was the predominant legume. Particularly on the north aspect slopes in winter and spring, however, this was supplemented to a large extent by subterranean clover (T. subterraneum).

The legume content of the pasture on the slopes in winter and spring was high compared with levels reported elsewhere for North Island hill country (Radcliffe et al., 1968; Gillingham and During, 1973; Suckling, 1975). This may be an effect of the previous generous topdressing history

Table 3.3 Seasonal and annual pasture production from topdressed and untopdressed slope strata (kgDM ha⁻¹)

Stratum	Season	North aspect		South aspect		L.S.D.
		Untopdressed	Topdressed	Untopdressed	Topdressed	
25° slope	Spring	3880	4080	2590	2710	
	Summer	2445	2695	2640	2560	
	Autumn	1460	1760	1200	1465*	222
	Winter	810	1010	680	765	
	Total	8595	9545	7110	7500	
45° slope	Spring	2200	2090	1805	1670	
	Summer	1460	1605	1440	1750	
	Autumn	1035	1090	1060	1050	
	Winter	670	890	405	445	
	Total	5365	5675	4710	4915	

* Significantly higher at 5% probability level.

Table 3.4 Pasture species composition (% by weight)
in each season

Pasture component	Season	North aspect			South aspect		
		Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
Legumes	Spring	2.7	32.0	31.7	5.0	16.1	24.4
	Summer	3.6	9.2	8.0	6.2	29.2	32.4
	Autumn	trace	4.6	3.2	2.2	17.2	16.6
	Winter	2.0	21.0	20.0	2.0	10.0	13.0
Grasses	Spring	86.5	53.2	46.2	89.1	69.4	45.5
	Summer	81.8	68.0	58.5	82.0	52.6	40.8
	Autumn	72.6	67.0	34.4	76.4	52.2	45.2
	Winter	92.0	66.0	52.0	86.0	65.0	55.0
Weeds	Spring	1.5	5.2	10.3	2.4	7.8	13.9
	Summer	2.4	6.8	10.6	1.0	8.4	13.0
	Autumn	3.0	5.0	11.0	0	9.4	14.8
	Winter	1.0	6.0	15.0	5.0	13.0	22.0
Dead matter	Spring	9.3	9.6	11.8	5.7	6.7	16.2
	Summer	12.2	17.2	18.2	10.8	9.8	13.8
	Autumn	24.4	23.4	51.4	21.4	21.2	23.4
	Winter	5.0	7.0	13.0	7.0	12.0	10.0

but is probably more a result of the recent series of favourable summer and autumn seasons that have dramatically increased legume persistence and seed germination over this critical period of the year. (New Zealand Ministry of Agriculture and Fisheries, unpublished trial results).

Pasture dead matter content increased from a minimum in winter and spring to a maximum in autumn on all strata. Pasture on steep slopes generally gave the highest proportion of dead matter at any time.

The proportional contribution of weeds to dry matter production was lowest on campsites and highest on 45° slopes at all times and remained relatively constant in relation to total dry matter production throughout the year.

3.3.1.4 Pasture P concentration

Results for the TP, DIP, and DOP contents of pasture are shown in Table 3.5. In each season for each P form, levels were highest in pasture from campsites and lowest in pasture from 45° slopes. Levels were similar in pasture from both aspects in spring and summer but generally higher on the south aspect in autumn and winter. The lower levels in autumn and especially on the north aspect are associated with more mature plant conditions but could partly be attributable to the low soil moisture content (McNaught, 1970). This does not explain the winter difference between aspects because the topsoils on both usually reach field capacity by the beginning of winter, i.e., the start of June (Gillingham, 1973).

The higher P concentrations in herbage from the south aspect in winter were most likely associated with the slower pasture growth rate, compared with that on the north aspect, because soil P levels on the slopes were similar on both aspects (Section 3.3.5) and the legume content, which would tend to boost mixed pasture P levels (McNaught, 1970), was greatest on north-facing slopes at this time.

Table 3.5 Amounts of P forms in pasture in each season

Season	Form of P	North aspect			South aspect		
		Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
Spring	TP ($\mu\text{g g}^{-1}$)	5300	5130	4550	5130	5320	4510
	S.E.	334	146	208	151	121	162
	DIP (% of TP)	81.7	76.8	72.3	83.6	74.4	75.3
	DOP (")	11.1	13.1	15.8	11.7	11.5	10.6
Summer	TP ($\mu\text{g g}^{-1}$)	4610	4440	4110	4730	4380	4320
	S.E.	178	117	111	146	103	96
	DIP (% of TP)	80.2	68.7	53.0	77.4	71.5	64.6
	DOP (")	8.9	15.1	14.6	6.8	9.4	11.6
Autumn	TP ($\mu\text{g g}^{-1}$)	4030	3550	2940	5120	4190	4420
	S.E.	84	167	264	204	210	252
	DIP (% of TP)	76.2	65.9	56.1	82.3	74.2	69.9
	DOP (")	8.2	5.4	11.9	4.8	11.2	9.3
Winter	TP ($\mu\text{g g}^{-1}$)	5680	4290	3740	6000	5190	4170
	S.E.	145	181	102	185	171	510
	DIP (% of TP)	69.4	76.2	71.6	72.5	77.8	78.2
	DOP (")	6.0	9.3	7.8	9.2	10.1	8.9

The total P content of the pasture from all but one site was high ($> 3500 \mu\text{gPg}^{-1}$) at all times of the year. The lowest value ($2940 \mu\text{gPg}^{-1}$) was measured on the north-facing, 45° slopes in autumn. This could be rated as bordering on deficient for ryegrass and white clover in an active growing condition (McNaught, 1970) but for the dominantly paspalum pastures should in this season be considered adequate.

The additional autumn pasture growth obtained by extra topdressing (Table 3.3) suggests that some P limitation exists, especially on the south aspect at this time of year.

The very high pasture P levels in winter on the campsites may have been induced by some synergistic effect (McNaught, 1970) of the associated high soil nitrogen levels characteristic of campsites (Popay, pers. comm.; Joblin et al., 1972). High NH_4^+ uptake from such areas could induce an associated high PO_4^- uptake to maintain the cation-anion balance in the plant. Although the pasture P levels are slightly higher the results are of the same order as those reported by Gillingham and During (1973) and fall within the range of 4500 to $7000 \mu\text{gPg}^{-1}$ considered a safe excess for ryegrass and white clover (McNaught, pers. comm.).

The very high level of DIP present in all pasture supports the early results of Harley et al. (1951) and later data of Jones and Bromfield (1969), and Bromfield and Jones (1972).

The DIP levels were highest in pasture from campsites and tended to decrease both in magnitude and as a proportion of total P as pasture total P decreased. This relationship is shown in Fig. 3.1. Bromfield and Jones (1972) similarly noted an increase in the proportion of water-soluble P as the total P level of plant material increased, an obvious reflection of a lower degree of conversion to organic P of inorganic P taken up by the plant.

There was no well-defined pattern to the variation in DOP level in

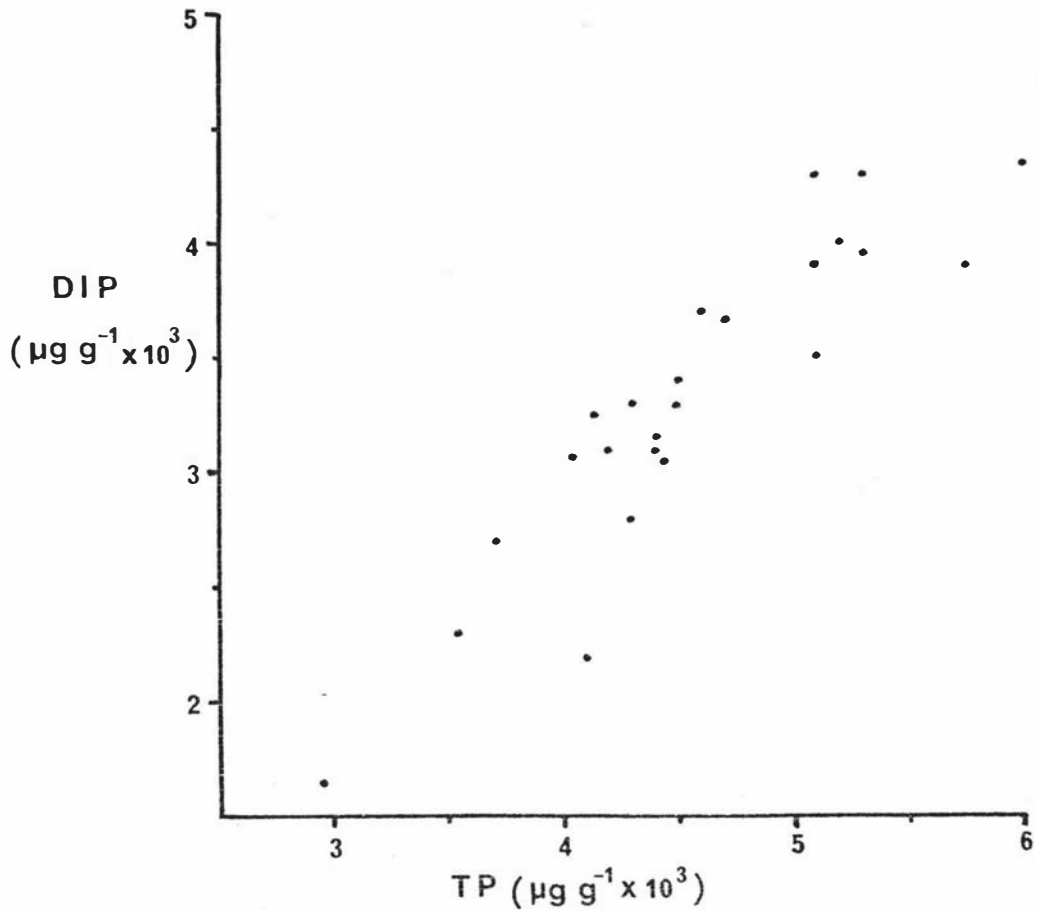


FIGURE 3.1 Relationship between the concentrations of DIP and TP in pasture.

pasture, being relatively constant in relation to TP level in the south aspect pasture but tending to be lower on the campsites than slopes on the north aspect.

3.3.1.5 Total P uptake by pasture

By combining mean pasture dry matter production and mean pasture total P concentration levels the total P uptake for each stratum was calculated (Table 3.6). On each aspect both seasonal and annual P uptake decreased sharply from campsites to 45° slopes. The seasonal and strata P uptake results were influenced predominantly by pasture growth rate. The exceptions were the south aspect 45° slopes in autumn and the south aspect 25° slopes in winter, where pasture P uptake was higher than on respective north slopes only because of the much higher pasture P concentrations on the south aspect at these times.

The results demonstrate the very marked seasonal nature of pasture P uptake on all strata, particularly on the north aspect where almost half the annual total uptake occurred in spring. Both spring and summer growth accounted for about 75% of total pasture P uptake on all sites.

3.3.2 Phosphorus return via dung

3.3.2.1 Total dung dry weight

One of the largest differences between strata within each aspect was in the total amounts of dung deposited by grazing sheep. This ranged from extremely high levels on campsites to very small amounts on steep slopes (Table 3.7).

There was no difference significant ($P \leq 0.05$) in the annual total weight of dung deposited on similar strata on each aspect. This was the case despite some relatively large differences in dung levels between aspects and therefore reflected the extreme within-strata variability of these results, as

Table 3.6 Seasonal and annual uptake of P by pasture on each stratum (kg ha^{-1})

Season	North aspect			South aspect		
	Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
Spring	26.4	19.9	10.0	25.7	13.8	8.1
S.E.	2.8	1.7	1.0	2.7	1.2	0.8
Summer	12.0	10.9	6.0	19.8	11.6	6.2
S.E.	1.0	1.4	0.6	0.8	1.1	1.3
Autumn	7.2	5.2	3.0	9.8	5.0	4.7
S.E.	0.8	0.9	0.8	1.3	0.8	0.8
Winter	10.1	3.4	2.5	7.7	3.5	1.7
S.E.	1.0	0.4	0.5	0.9	0.5	0.5
Total	55.7	39.4	21.5	63.0	33.9	20.7
S.E.	5.6	4.4	2.9	5.7	3.6	3.4

Table 3.7 Seasonal and annual deposition of dung on each stratum (kgDM ha⁻¹)

Season	North aspect			South aspect		
	Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
Spring	2240	305	35	3975	619	90
S.E.	665	82	8	502	52	35
Summer	4475	542	22	5850	571	148
S.E.	1288	59	11	1434	108	54
Autumn	2345	171	75	3900	278	44
S.E.	893	20	15	927	51	12
Winter	1245	178	25	1170	155	34
S.E.	415	46	11	245	36	9
Total	10305	1195	157	14895	1625	316
S.E.	3261	207	45	3108	247	110

demonstrated by the associated high standard errors.

Seasonal dung distribution patterns were similarly variable, although on the south aspect 25° slopes in spring ($P \leq 0.05$) and 45° slopes in summer ($P \leq 0.10$) dung accumulation was significantly higher than on the respective north aspect sites at those times.

The greater deposition of dung on south aspect strata suggest, despite the high variability of the results, that this may have been a real difference which could possibly be detected by greater sample replication.

Although it cannot directly be concluded from the data, it is possible that such a difference between aspects could exist, considering the difference in overall topography of the two paddocks (Table 3.1). The smaller proportion of campsites and 25° slopes on the south aspect implies, with the natural preference of sheep for easier slopes, that the stocking density on these areas would have been high, relative to the north aspect. With the large proportion of steep, south-facing slopes, however, sheep were also forced to graze these to a greater extent than slopes of similar steepness in the north paddock. Dung accumulation would tend therefore to be also relatively higher on the steep south aspect slopes. It is possible that paddock topographical balance may in this way be an influential factor modifying dung return patterns, not only to campsites but to all parts of a paddock.

The dung accumulation on camps and 25° slopes, in summer in particular, appeared to be high relative to the results in spring. Considering both pasture production levels (Table 3.2) and stock-grazing days (i.e. 3332 stock-grazing days in spring, compared to 2803 in summer on the north aspect; 3298 compared to 1970, respectively, on the south aspect (Appendix III) it could be expected that dung deposition would be lower in summer than in spring, especially on the north aspect. The totals calculated on a paddock

basis using data from Table 3.1, however, show that this was not so, i.e., the estimated mean quantity of dung per hectare on both aspects was higher in summer than in spring, i.e., 1207 and 1036 kg ha⁻¹ on the north and south aspect, respectively, in summer compared with 628 and 805 kg ha⁻¹, respectively, in spring.

Bromfield (1961) also recorded relatively high summer faecal output, a feature that may be associated with the generally higher dry matter content and lower digestibility of summer and autumn pasture, compared with that in spring, (Minson et al., 1960; Hutton, 1962).

3.3.2.2 Estimated dung distribution pattern

Dung return to the various strata in the present trial was estimated as the mean weight on unit area of land per year (kg ha⁻¹). In reality, however, the time interval between successive accumulations of dung on the same small unit of land may be many years and especially so on very steep sites (discussed later).

On flat land, Peterson et al. (1956a) concluded that the dung distribution pattern by grazing cattle was more similar to that of a negative binomial than a Poisson curve. On hill paddocks the effect of topography was to produce an even more skewed pattern of dung return (Gillingham and During, 1973). It is likely that in the present trial the system of sampling according to the stratification of slopes reduced considerably the distorted dung distribution so that the within stratum return was much nearer that of a normal distribution pattern. The fixed plot method of sampling, however, prevented any valid estimate being made of the true within-strata dung distribution pattern. Although this distribution may not be known, some assumptions can be made that are likely to be close to the true situation and which serve to demonstrate the order of frequency of dung return to the three strata studied.

In order to estimate the areas covered by dung the following assumptions were made: (i) stock grazed on each stratum in direct proportion to the pasture production level at the estimated annual mean utilization level (1 stock unit equivalent to 500 kg consumed pasture dry matter); (ii) each animal defaecated an average of 6 times per day, dung covering 100 cm^2 on each occasion and totalling 540g dry dung per day (based on data of Sears and Newbould, 1942; Herriott and Wells, 1963); (iii) dung was distributed within each stratum in a Poisson manner; and (iv) the mean excretal density (i.e., total dung per total area) at 100% coverage was 10.

Using these assumptions, and the measured total dung weights (Table 3.7), the times taken for dung return to cover different proportions of each stratum were calculated (Table 3.8). These estimates illustrate the striking difference in the time scales of dung return intervals on the different strata.

On campsites which received high levels of dung, it would still take 7.0 years and 4.8 years to cover 20% of their area on north and south aspects, respectively. Obviously during this time some sites within this 20% area will have received dung several times. Similarly, the bulk of each campsite (85%) will take 11.4 and 8.0 years, respectively, to receive P via dung.

The most significant results, however, are those for the slopes which occupy the bulk of any hill paddock. On 25° slopes it would take many years (60.0 on north and 43.6 on south) for even 20% of the stratum area to be covered. On 45° slopes there was effectively a nil return of P via dung to the greater part of the area. In order to place these figures in perspective it could be interpreted that to date most parts of the 25° slopes and almost all of the 45° slope stratum have never received P via dung.

Table 3.8 Estimated time required for dung from grazing sheep to completely cover various proportions of each stratum

Parameter	North aspect			South aspect		
	Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
Estimated grazing capacity (stock units ha ⁻¹)	14.9	11.8	6.8	16.2	10.2	6.3
Time required (yr) to cover						
20%	7.0	60.0	445.0	4.8	43.6	228.8
85%	11.4	99.6	736.6	8.0	72.6	379.2
100%	109.2	949.4	7003.4	75.8	691.6	3620.0

3.3.2.3 Dung P content

3.3.2.3.1 Comparative dung preparation and analysis. The dung samples derived from "improved" and "unimproved" pasture differed in appearance. The sample from improved pasture was relatively dark and the pellets compact whereas that from the unimproved pasture was lighter in colour and contained noticeable undigested, fibrous plant residues. The difference in dry matter content (Table 3.9) shows that the density of the "improved" sample was more than twice that of the "unimproved" sample. This difference was probably the main factor in the greater release of TDP from whole pellets of the "unimproved" sample, despite the higher TP level of the "improved" dung (determined on dried and ground material). This suggests that the rate of P release from dung in the field may be markedly affected by the density as well as the P content of the material.

Results from analysis of whole pellets of dung were extremely variable, as indicated by the separate results for subsamples (a) and (b) in Table 3.9. This variability also existed in oven-dried, freeze-dried, and frozen whole samples, and similarly in measurements of TIP and TP.

For further analysis, all samples were crushed and mixed. In addition the oven-dried and freeze-dried samples were passed through a 2-mm mesh. This pretreatment markedly improved sample replication.

Sample preparation method had no effect on the TP content of dung from either source or on the level of TIP in the dung from "unimproved" pasture (Table 3.10). Both drying methods did appear to cause a slight increase in the inorganic P level of dung from "improved" pasture, and conversely a decrease in the derived total organic P value, compared with that in the fresh condition. This difference was not confirmed when TIP was determined by the Anderson-Mehta technique. Results by this latter method were similar

Table 3.9 Dry matter, TDP and TP content of whole, undried sheep dung from "improved" compared with "unimproved" pasture

Sample	Dry matter content (% by weight)	TDP content ($\mu\text{g g}^{-1}$)		TP content** ($\mu\text{g g}^{-1}$)
		(a)*	(b)*	
Improved	52.8	820	970	7830
Unimproved	23.4	1000	1690	6940

* (a) and (b) subsamples reflect variability in results.

** determined on dried and ground material.

Table 3.10 Amounts of P forms ($\mu\text{g g}^{-1}$) in variously prepared forms of dung as determined by two methods of analysis

Form of P	Sample	Oven-dried	Freeze-dried	Frozen	Fresh
<u>Ignition method</u>					
Total inorganic P	Improved	6510	6510	6020	5860
	Unimproved	4280	4360	4340	4330
Total organic P	Improved	1360	1360	1600	1970
	Unimproved	2590	2540	2470	2610
Total P	Improved	7870	7870	7620	7830
	Unimproved	6870	6900	6810	6940
<u>Anderson-Mehta method</u>					
Total inorganic P	Improved	6510	6350	6270	6230
	Unimproved	4770	4560	4610	4440
Total organic P	Improved	930	960	950	1080
	Unimproved	1390	1590	1290	1430
Total P	Improved	7440	7310	7220	7310
	Unimproved	6160	6150	5900	5870

for all preparation techniques and to those obtained by acid extraction (Walker and Adams, 1958).

Total P values obtained by the Anderson-Mehta procedure, however, were slightly lower than those measured by the ignition method, especially for the "unimproved" samples. The reason for this difference remains unexplained because subsequent ignition and shaking of the Anderson-Mehta dung residue with 1N H_2SO_4 failed to extract any significant additional P.

The method of dung sample preparation was also tested for any effect on the level of water-extractable P. As shown in Table 3.11, this had no significant effect on either the amounts of DIP or DOP extracted. Smaller amounts of DIP were extracted from the "unimproved" than from the "improved" dung samples but the DOP content of both was similar.

In order to evaluate the relative ease of extraction of water-soluble P from dung, oven-dried samples were subjected to both a sequential and a prolonged extraction. Water was renewed ($40 \text{ ml g}^{-1} \text{ DM}$) for each of the four-successive extractions totalling 6 hours, compared with the unchanged extract shaken for a similar period. Considerably more DIP was extracted from both dung samples by the sequential compared with the continuous extraction (Table 3.12). The inorganic P content of the fourth extract was in both cases still appreciable, indicating that even further P release was likely. The total DIP extracted from both samples (expressed as a proportion of the total inorganic P level) was similar, i.e., 56.3% of the TIP from the "improved" sample and 58.6% from the "unimproved" sample. This suggested that the overall rate of DIP release was proportional to the level of TIP initially present.

In contrast to the data for DIP the levels of DOP extracted by both sequential and continuous extraction methods were similar and comprised a smaller proportion of the total organic P present in both dung samples.

Table 3.11 Amounts of water-extractable P ($\mu\text{g g}^{-1}$)
in variously prepared forms of dung

Form of P	Sample	Oven-dried	Freeze-dried	Frozen	Fresh
DIP	Improved	1850	1950	1860	1860
	Unimproved	1380	1170	1300	1250
DOP	Improved	360	290	490	400
	Unimproved	320	400	490	380

Table 3.12 Water-extractable P removed from oven-dried, crushed dung by both repeated and prolonged extractions

Form of P	Sample	Repeated				Total	Prolonged (6 hr)
		First extract (1 hr)*	Second extract (1 hr)	Third extract (2 hr)	Fourth extract (2 hr)		
DIP	Improved ($\mu\text{g g}^{-1}$)	1600	825	750	490	3665	2330
	(as % of TP)	43.6	22.5	20.5	13.4		63.6
	Unimproved ($\mu\text{g g}^{-1}$)	1000	560	560	390	2510	1370
	(as % of TP)	39.9	22.3	22.3	15.5		54.6
DOP	Improved ($\mu\text{g g}^{-1}$)	270	65	50	75	460	440
	(as % of TP)	58.7	14.1	10.9	16.3		95.6
	Unimproved ($\mu\text{g g}^{-1}$)	70	135	30	30	265	210
	(as % of TP)	26.5	50.9	11.3	11.3		79.2

* Duration of extraction period.

In a similar experiment, Bromfield (1961), made five successive water extractions (80 ml g^{-1} DM shaken for 1 hours) and related the total extractable inorganic P to TIP, defined as the inorganic P extracted by shaking 1g of dung with 80 ml of 0.2N HCl for 1 hours. In dung containing $1260\mu\text{g P g}^{-1}$ of TIP a total of $3720\mu\text{g P g}^{-1}$ (equivalent to 29.5%) was water soluble. At TIP levels of 3400 and $400\mu\text{g P g}^{-1}$ this increased to 57.0% and 60.0%, respectively. This contrasts with the results of Floate (1970a) who in five successive extractions removed water-soluble P equivalent to 67% of the TIP present when this was at a high level ($11600\mu\text{g P g}^{-1}$), and equivalent to 99% or more when the TIP level was $8430\mu\text{g P g}^{-1}$ or less. The water-soluble P extraction procedure used was not described. As noted in Section 2.4.2.4, however, neither the results from the present study nor those reported by Bromfield (1961) or Floate (1970a) support the contention of Barrow (1975) that faecal P is present as dicalcium phosphate.

In the present study the lower water:dung ratio, longer shaking time used for extraction of water-soluble P, and the stronger acid (i.e., 1N H_2SO_4 compared to 0.2N HCL) used to define TIP preclude any direct comparison of results with those of either Bromfield (1961) or Floate (1970a). The close similarity between TIP levels measured by both 1N H_2SO_4 and the Anderson-Mehta methods, however, suggests that the stronger acid extraction (1N) more accurately represents the "true" inorganic P present in dung.

For this reason 1N H_2SO_4 was selected as the extractant for determining the inorganic P content of dung.

Freeze-drying and sieving ($< 2\text{mm}$) were chosen as the standard method of sample preparation on the basis that:

- (a) a dried sample was preferable for better mixing and sample replication; and
- (b) although the results from oven-dried and freeze-dried samples were generally similar, freeze-dried samples gave the best comparison with fresh dung when all analyses were considered.

3.3.2.3.2 Field trial. The TP content of dung was at a maximum in spring and a minimum in summer on both aspects (Table 3.13). This contrasts with the total weight of dung deposited in these seasons, being lower in spring than in summer. A similar inverse relationship was reported by Bromfield (1961). The sharp rise in TP content of dung on the north aspect in late autumn was probably associated with the sudden boost in pasture clover growth during this period on all north aspect strata following persistent autumn rain. The preferential grazing by stock of new growth would have been a major factor increasing dung TP content because a high faecal P level is associated with periods of flush growth (Bromfield, 1961).

The south aspect maintained a higher pasture legume content during autumn (Table 3.4) and therefore the new autumn growth did not provide such a change in diet as it did for stock on the north aspect. Consequently, dung TP levels did not exhibit the same seasonal pattern of variation.

In view of the increase in TP content of dung on the north aspect in late autumn it appears that the mean TP concentration in pasture, as represented by the early autumn harvest and used to derive mean TP uptake by autumn pasture (Table 3.6), may have slightly underestimated the real situation.

Dung contained a significant proportion of DIP. This proportion was relatively constant, in most cases, being between 20 and 30% of TP, or 25 to 40% of TIP, although it was lower on each aspect in summer when TP was at a minimum. The dung collected in early spring from the south aspect also had a relatively low DIP content. The DOP content in dung from the north aspect was lowest in autumn and highest in late winter. On the south aspect these extremes occurred in late summer and early spring, respectively. At all times, however, DOP remained a relatively constant proportion of TP.

Table 3.13 Amounts of P forms in dung collected at each season

Season	Sampling date	North aspect				South aspect			
		TP ($\mu\text{g g}^{-1}$)	TIP (% TP)	DIP (% TP)	DOP (% TP)	TP ($\mu\text{g g}^{-1}$)	TIP (% TP)	DIP (% TP)	DOP (% TP)
Spring	1.10.75	14655	83.0	22.8	3.2	14585	79.0	14.4	4.9
	S.E.	355				1025			
	1.12.75	12245	75.0	26.8	2.7	14920	75.0	28.8	2.7
	S.E.	590				720			
Summer	19.1.76	7315	68.5	14.3	2.9	10865	79.7	20.6	3.0
	S.E.	405				290			
	1.3.76	8640	74.0	29.8	2.3	8680	70.0	8.0	1.7
	S.E.	1030				485			
Autumn	20.4.76	8270	75.7	20.7	1.9	11225	83.4	24.5	2.3
	S.E.	430				1380			
	1.6.76	14155	73.4	26.9	2.8	10365	79.7	33.4	2.7
	S.E.	420				210			
Winter	12.7.76	10700	77.9	24.4	2.4	9780	76.1	22.1	3.4
	S.E.	685				490			
	1.9.76	10530	78.6	31.3	7.7	11925	86.4	23.8	1.4
	S.E.	470				555			

The TIP content of dung from the north aspect ranged from 68.5 to 83.0% of the TP and from 70.0 to 86.4% of TP on the south aspect. These results are similar to those reported by Bromfield (1961) from dung with a TP content of $16,600 \mu\text{g P g}^{-1} \text{ DM}$ (76% TIP), by Martin and Molloy (1971) using dung of $15,000 \mu\text{g P g}^{-1} \text{ DM}$ TP level (77% TIP), and by Barrow (1975) for dung of $20,800 \mu\text{g P g}^{-1} \text{ DM}$ TP content (89% TIP). In each case, TIP was determined by different methods.

The lowest proportion of TIP (i.e. 68.5% of TP) was measured in dung from the north aspect in early summer. This also represented the lowest concentration of TIP recorded ($5010 \mu\text{g P g}^{-1}$). Bromfield (1961) noted a similar proportional decrease, e.g., at low TP levels of 6000 (57% TIP) and 1680 (23% TIP) $\mu\text{g P g}^{-1} \text{ DM}$, respectively.

3.3.2.4 Total P return in dung

Using the results from Tables 3.7 and 3.12, the TP return via dung to each strata in each season was calculated (Table 3.14).

The quantity of P returned in each case was dominated by the dung distribution pattern. The associated high variability of those results ensured that the standard errors of estimate of the derived levels of P return were correspondingly high. Consequently, although seasonal TP returns to south aspect strata were in most cases markedly higher than to respective north aspect sites, the differences were not statistically significant.

The importance of dung as a pathway for P return to the soil was obviously greatly affected by topography. The very biased pattern of dung return meant that on campsites faecal P supplied of the order of two to three times that necessary for annual pasture uptake. In contrast, P return to the slopes, which occupied the greatest proportion of each paddock, was sufficient for only a fraction of pasture needs. This fraction appeared to decrease sharply with increasing steepness of slope.

Table 3.14 Seasonal and annual return of P in dung to each stratum (kgDM ha⁻¹)

Season	North aspect			South aspect		
	Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
Spring	30.2	4.1	0.4	58.6	9.1	1.3
S.E.	11.1	1.4	0.1	14.3	1.8	0.7
Summer	35.7	4.3	0.2	57.2	5.6	1.4
S.E.	12.8	1.2	0.1	18.7	1.5	0.7
Autumn	26.3	1.9	0.8	43.7	3.1	0.5
S.E.	12.2	0.4	0.3	16.7	1.0	0.2
Winter	13.2	1.9	0.3	12.7	1.7	0.4
S.E.	6.1	0.7	0.1	3.9	0.6	0.1
Total	105.4	12.2	1.7	172.2	19.5	3.6
S.E.	42.2	3.7	0.6	53.6	4.9	1.7

3.3.3 Phosphorus return via pasture litter

3.3.3.1 Total litter dry weight

In marked contrast to dung return patterns, the accumulation of litter was much more uniform on all strata in each season (Table 3.15). This reflected the evenness of grazing pressure over the whole of each paddock. A relatively high amount of litter accumulated on campsites in summer and therefore the annual total for these areas greatly exceeded that for either the 25° or 45° slopes which did not differ significantly in this respect.

In general more litter was collected from the south than from the north aspect campsites, except in spring, but litter accumulation on the north slopes exceeded that on the south in each season.

The slightly higher litter accumulation on the south aspect campsites over most of the year could partly be an effect of the similarly higher dung accumulation on these areas because it is known that stock tend to reject fouled pasture (Norman and Green, 1958).

On the other hand, the greater amount of pasture litter on the north aspect slopes in spring, summer, and autumn could reflect the probably lower grazing pressure on these compared with corresponding south aspect sites due to the difference in overall paddock topography (as discussed in Section 3.3.2.1). It is likely, however, that litter accumulation in summer and autumn was also accelerated by lower soil moisture and higher temperatures on the north slopes than on the south slopes. These factors would induce advanced maturity and senescence with a corresponding increase in plant and dead matter. The botanical composition of litter also varied with season and between campsite and other strata (Appendix IV).

The most striking aspect of the litter composition was that although dry matter production of flat weeds, and more particularly of clovers, was

Table 3.15 Seasonal and annual pasture litter accumulation on each stratum (kgDM ha⁻¹)

Season	North aspect			South aspect		
	Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
Spring	457	347	372	290	243	240
S.E.	57	28	13	30	17	32
Summer	1283	876	581	1571	543	412
S.E.	215	90	30	165	21	44
Autumn	646	539	472	830	301	311
S.E.	115	48	18	81	11	30
Winter	136	213	253	260	203	220
S.E.	28	27	60	52	42	16
Total	3152	1975	1678	2951	1290	1183
S.E.	415	193	121	328	91	122

at times marked (Table 3.4), these formed an insignificant proportion of the total litter collected in any season. It must be concluded, therefore, that they were more selectively grazed by sheep than were the grass components of the pasture.

It may be argued that the more upright grasses offered better protection to older leaves around and within the base of a plant and were less efficiently grazed than the more prostrate legumes and flatweeds. It seems remarkable that even during the fast growth periods of spring and summer, when clover and flatweeds produced approximately 40% of total growth on the slopes, virtually none remained unutilized by stock.

It is recognised that incorporation and decomposition of plant material, e.g., by slugs (Agriolimax reticulatus. Müll.) and earthworms (Allobophora caliginosa and Lumbricus rubellus) may be very active during the year, especially in winter and spring, and particularly on the legume component (Charlton, pers. comm., Sharpley and Syers, 1976). The 4 to 6 week interval between litter collections could have provided an opportunity for soil invertebrates to decrease the quantity of surface litter or for any more rapid decomposition of clover than grass material to occur. It seems unlikely, however, that all dead legume and flatweed material could have been eliminated if it provided any significant portion of the total pasture unutilized by stock.

3.3.3.2 Litter P content

The TP content of litter was generally highest on campsites and lowest on 45° slopes on each aspect (Table 3.16). On both aspects, the litter TP content was highest in winter and spring. It was lowest on the north aspect campsite in summer and on the north aspect slopes in autumn when the south aspect pasture litter was similarly at its lowest TP content. The seasonal and strata variability was similar to that for pasture (Table 3.5).

Table 3.16 Amounts of P forms in litter collected
at each season

Season	Form of P	North aspect			South aspect		
		Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
Spring	TP ($\mu\text{g g}^{-1}$)	5390	4440	2850	5250	2970	2810
	S.E.	92	187	181	367	155	228
	DIP (% of TP)	71.3	77.9	82.2	75.0	74.4	71.0
	DOP (")	6.2	9.0	7.5	12.9	9.4	9.2
Summer	TP ($\mu\text{g g}^{-1}$)	3740	3870	2960	3570	3500	3140
	S.E.	106	11	409	172	241	55
	DIP (% of TP)	76.4	83.0	73.2	86.9	87.4	69.0
	DOP (")	7.8	9.8	12.2	7.6	8.8	19.4
Autumn	TP ($\mu\text{g g}^{-1}$)	4640	3430	2180	2350	2980	2490
	S.E.	96	255	207	221	253	204
	DIP (% of TP)	37.3	37.3	34.4	38.7	42.9	40.6
	DOP (")	4.1	7.3	8.4	9.8	7.0	11.7
Winter	TP ($\mu\text{g g}^{-1}$)	5210	4320	2830	5650	4130	2770
	S.E.	424	489	635	659	260	502
	DIP (% of TP)	34.3	45.0	49.4	38.1	52.6	48.7
	DOP (")	2.5	5.8	5.6	3.6	3.8	4.9

The two sets of results cannot be directly compared as the pasture used to produce "litter" was in a pregrazed condition when shaded, whereas the pasture for analysis was produced after pretrimming and allowing regrowth. The litter, therefore, was derived from more mature pasture. Consequently, the generally lower TP content of litter than of the pasture must partly be attributed to the difference in initial material as well as to some translocation of P from herbage during senescence induced by shading (Williams, 1955).

The DIP content of litter, both in P concentration and as a proportion of TP, was high in both spring and summer but much lower in autumn and winter. In contrast, DOP was relatively constant, except in winter when both the level and proportion of TP were at a minimum for the year.

The DIP and DOP levels presented in Table 3.15 were obtained from finely-ground, freeze-dried material. For comparison, DIP and DOP from whole, freeze-dried material was determined. Autumn litter was used for this purpose (Table 3.17).

The amount of DIP extracted from whole samples ranged from 62.4 to 80.6% of that measured in finely-ground samples. This is a high level relative to the difference in surface area of the two samples. The cortical and epidermal cells of the predominantly stem material would almost certainly have a higher P content than the dead xylem cells and possibly more than the pith cells (Bieleski, pers. comm.). Drying, in this case freeze drying, would have ruptured some of these cells and thus the effect of grinding may be only to provide shorter diffusion paths for the release of P.

The extent to which this same effect occurs in the field will depend on the degree of drying experienced by dead plant material before it collapses to the soil surface. Such drying is more likely to occur in summer or autumn than in winter or spring, although freezing of plant tissue

Table 3.17 Effect of sample condition on amounts of water-extractable inorganic (DIP) and organic P (DOP) in autumn litter

Sample condition	Form of P	North aspect			South aspect		
		Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
	DIP						
Finely ground	($\mu\text{g g}^{-1}$)	1728	1284	752	910	1281	1011
Whole	($\mu\text{g g}^{-1}$)	1282	871	469	734	848	670
	(as % of finely ground)	74.2	67.8	62.4	80.6	66.2	66.3
	DOP						
Finely ground	($\mu\text{g g}^{-1}$)	190	251	185	233	214	291
Whole	($\mu\text{g g}^{-1}$)	174	116	71	153	280	113
	(as % of finely ground)	91.6	46.2	38.4	65.7	130.8	38.8

as could occur on both aspects in winter would achieve the same effect. Following such preconditioning, it is possible that regular rainfall from late autumn onwards could release an appreciable proportion of the total DIP from dead pasture material.

The DOP released from whole litter was variable both in amount and as a proportion of that extracted from similar finely ground material. In all samples however DOP provided only a small proportion of total water-extractable P and therefore in the field situation P leached directly from litter may be considered to be predominantly DIP.

3.3.3.3 Total P return in litter

The estimated annual TP return to the soil surface via litter was highest on campsites and lowest on 45° slopes on both aspects (Table 3.18). This difference was significant on both north ($P \leq 0.10$) and south aspects ($P \leq 0.05$). The same pattern of return applied within each season, the difference being significant ($P \leq 0.05$) on the north aspect in spring, summer and autumn but only in autumn on the south aspect ($P \leq 0.05$).

Although the TP return to the south aspect campsites was higher in summer and winter than to the north campsites, the difference was not significant. Similarly, although annual litter P return was higher to all the north than to respective south slopes, the difference was significant only between the 25° slopes.

The level of TP return via litter was remarkably uniform over the whole trial considering the range in litter production and P concentration of pasture on the various strata. The annual TP return in litter, however, did tend to be proportional to pasture P uptake and so contributed approximately 15 to 20% of annual pasture requirements on each stratum.

Table 3.18 Seasonal and annual return of total P in litter to each stratum (kg ha^{-1})

Season	North aspect			South aspect		
	Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
Spring	2.5	1.5	1.1	1.5	0.7	0.7
S.E.	0.4	0.2	0.1	0.8	0.4	0.4
Summer	4.8	3.4	1.7	5.6	1.9	1.2
S.E.	1.1	0.2	0.3	0.7	0.2	0.1
Autumn	3.0	1.9	1.0	2.0	0.9	0.8
S.E.	0.6	0.3	0.1	0.3	0.1	0.1
Winter	0.7	0.9	0.7	1.5	0.9	0.6
S.E.	0.2	0.2	0.3	0.5	0.3	0.2
Total	11.0	7.7	4.5	10.6	4.4	3.3
S.E.	2.3	0.9	0.8	2.3	1.0	0.8

3.3.3.4 Estimated pasture utilization by sheep

The degree of pasture utilization by stock is generally expressed as a percentage of the feed offered (Campbell, 1966). This is usually on a per-grazing basis and so total pasture utilization over a longer period can only be determined by summing the per-grazing intake by stock, measured as the difference before and after grazing, of standing pasture dry matter, and relating it to total pasture growth over the same period. This method is likely to overestimate pasture utilization by stock unless before and after grazing measurements are made by collecting all above ground pasture dry matter, i.e., including dead material.

In contrast, seasonal pasture utilization in the present study was estimated by subtracting herbage litter (total less root material) from the total pasture production measured by the trim technique. While the pasture cutting technique did not exactly simulate the grazing regime, particularly in winter when there were two grazings but only one pasture cut, it was considered to provide a useful relative comparison of grazing efficiency between different strata and seasons.

Average annual pasture utilization was higher on 25° slopes than on any other strata although utilization was surprisingly high on all strata in spring (Table 3.19). On the campsites this decreased in summer and autumn and increased again in winter. A similar fluctuation occurred on the north aspect slopes, although the rise in winter was less marked. On the south-facing slopes, however, the utilization level decreased continuously from spring to winter.

The above variations in grazing efficiency by stock closely followed the changes in pasture physiological condition. Because of vigorous vegetative growth in spring on both aspects (Table 3.2), little senescent material formed even though plants in some areas were relatively rank.

Table 3.19

Estimated seasonal and annual utilization of pasture
on each stratum by grazing sheep

Season	Aspect	Campsites			25° slopes			45° slopes		
		Pasture Production (kgDM ha ⁻¹)	Herbage Litter (kgDM ha ⁻¹)	Pasture* Utiliz. (%)	Pasture Production (kgDM ha ⁻¹)	Herbage Litter (kgDM ha ⁻¹)	Pasture Utiliz. (%)	Pasture Production (kgDM ha ⁻¹)	Herbage Litter (kgDM ha ⁻¹)	Pasture Utiliz. (%)
Spring	North	4975	361	92.7	3880	250	93.6	2220	275	87.5
	South	4990	224	95.5	2590	143	94.5	1805	167	90.7
Summer	North	2600	1174	54.9	2445	671	72.6	1460	467	68.0
	South	4195	1494	64.4	2640	438	83.4	1440	326	77.4
Autumn	North	1785	569	68.1	1460	394	73.0	1035	360	65.2
	South	1915	763	60.2	1200	232	80.7	1060	246	66.8
Winter	North	1780	102	94.7	810	164	79.8	670	176	73.7
	South	1290	227	82.4	680	150	77.9	405	164	59.5
Total	North	11140	2206	79.2	8595	1479	82.8	5365	1278	76.2
	South	12390	2708	77.2	7110	963	86.5	4710	903	80.8

* derived as pasture production less herbage litter accumulation and expressed as a % of pasture production.

The accumulation of dead pasture material in summer was largely a reflection of the efficiency of spring grazing in maintaining plants in a vegetative condition for as long as possible. This effect carried over into early autumn when death of plants, due to dry soil conditions, reduced grazing efficiency still further as stock rejected such material. The onset of fairly persistent autumn rain halted senescence of most species on north-facing slopes. As a consequence, further contributions to pasture litter in early winter came predominantly from previously upright stems and leaves collapsing to the soil surface. On the south aspect, pasture growth on steep slopes in winter was very slow as a result of the generally low soil temperatures during this period of the year at Whatawhata (Gillingham and Bell, 1977). Consequently, plant senescence continued, resulting in a lower proportion of utilized pasture than in any other season.

The slightly higher utilization of pasture on the south than on the north aspect slopes in summer and autumn could partly be attributed to the difference in maturity and species composition, resulting from the differing microclimate. The drier north aspect conditions produced more pasture dead matter (Table 3.4) which would have been preferentially ungrazed by stock compared with pasture of higher legume content on the south aspect.

Using the paddock details in Table 3.1 and results from Table 3.19 an overall pasture utilization level was calculated for the year. This was estimated to be 81% for the north aspect paddock and 83% on the south. This is very high by hill country standards (Eadie, 1970) but not unrealistic in relation to other estimates for grazed flat-land pastures. Smetham (1973) quotes 80% as a level obtained by better dairy farmers in New Zealand and Hutton (1973) 90% as that attainable.

By using results from Tables 3.1 and 3.18, and Appendix III the amount

of pasture grown on each stratum that was utilized by stock was calculated. Therefore the proportional contribution of each stratum to grazing stock in each paddock was also derived. Campsites, 25° slopes, and 45° slopes were estimated to contribute 26.0, 59.1 and 14.9%, respectively, of total carrying capacity on the north aspect and 20.6, 50.4, and 29.0%, respectively, on the south aspect paddock. These values related to the percentage area occupied by each stratum in each paddock (Table 3.1) enabled a % carrying capacity:% area ratio to be derived. This was 1.29, 1.06, and 0.62, respectively, for strata on the north aspect and 1.69, 1.11, and 0.69, respectively, for south aspect strata. These ratios show, as suggested in Section 3.3.2.1, that all strata on the south aspect were subjected to proportionately higher grazing pressure than similar strata on the north aspect.

In managing the present trial it was intended that grazing should give a high level of pasture utilization to all strata within each paddock at all times of the year. In general this was achieved, and in fact grazing pressure was higher than would be applied by a hill farmer, as evidenced by mean stock weight losses during some grazing periods (Appendix III). The levels of pasture utilization estimated for each aspect should therefore be considered as an upper limit for this type of country and unlikely to be exceeded in similar conditions with the grazing system used.

3.3.4 The phosphorus cycle

3.3.4.1 Annual uptake and return of P

By comparing the annual TP uptake by pasture and the TP return in both pasture litter and in dung a net P balance was derived for each stratum (Fig. 3.2).

The large surplus of total P above annual pasture needs that occurred

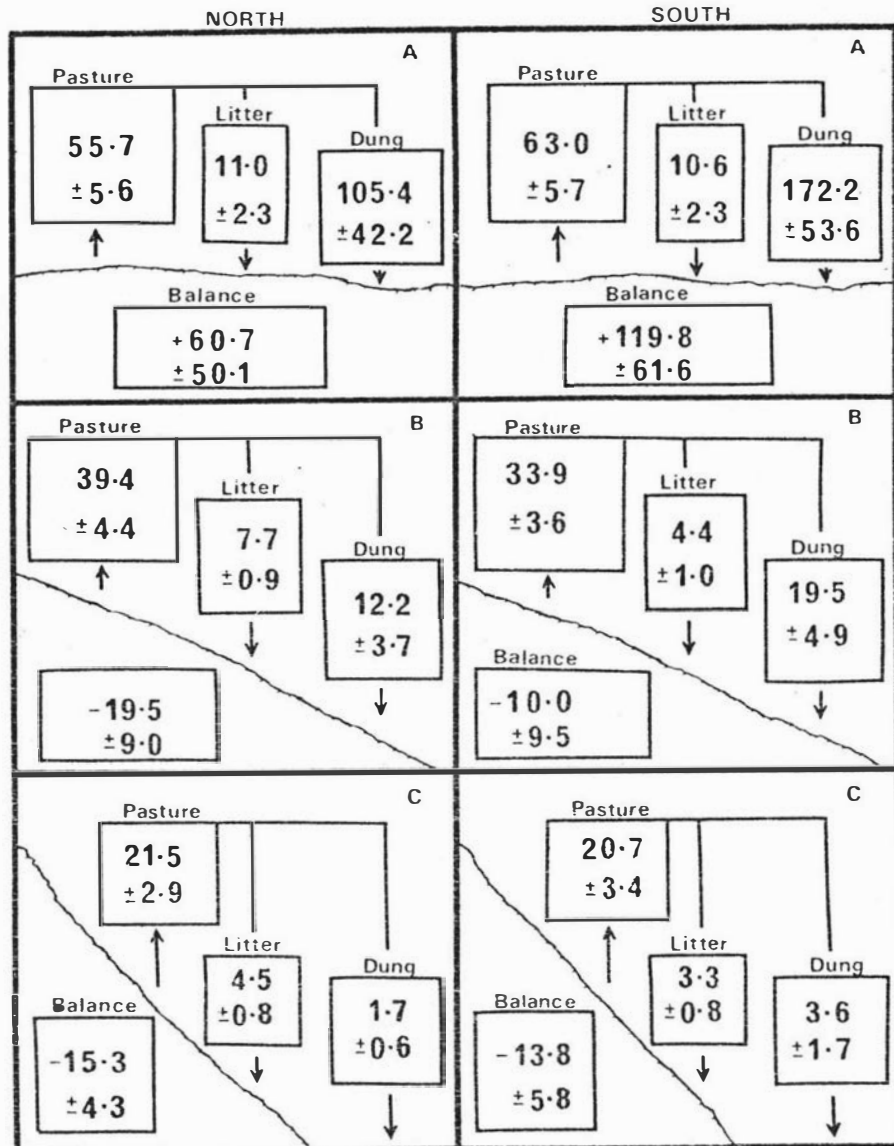


FIGURE 3.2 Annual total P uptake by pasture and total P return in litter and dung, and net total P balance (kg ha^{-1}) including Standard Errors of estimate for each value; A = campsites, B = 25° slopes, and C = 45° slopes.

on campsites was a direct result of the disproportionately high P return in dung. Conversely, the total P return to the slopes was in all situations less than that required to compensate for pasture uptake. The net P losses from all slopes were not significantly different but on the 45° slopes this represented a high proportion of annual P uptake. The relatively high loss from 45° slopes was largely due to the very low P return in dung even though pasture utilization levels were high.

This strong topographical influence on the dung, and therefore P, return to various hill-country sites was earlier indicated in the results of Gillingham and During (1973). Although their strata "C" and "D" occupied the steepest 63.4% of the paddock, which relates in proportion to the 45° slopes in the present study, the topography of these strata was only moderately steep and therefore in actual steepness was similar to the 25° slope group. The estimated P returns in dung to strata "C" and "D" were 27.5 and 15.8 kg P ha⁻¹ yr⁻¹, respectively, which, together with pasture production levels, are more similar to those for the 25° than for the 45° slopes, as shown in Fig. 3.2. This suggests that surface slope rather than relative accessibility, or topographical balance, within a paddock is the major factor affecting the level of P return as dung to any particular site.

It appears, however, that relative accessibility may be more important in affecting dung concentrations in camp areas. The camp area described by Gillingham and During (1973) occupied only 6.4% of the total paddock area but was surrounded by a large adjacent area of similar contour ("B" stratum of 27.5% total area) which received relatively high dung returns and so tended to spread the effective camp area. Consequently, dung return to the campsite itself was lower and the estimated P surplus was less than on the much more defined camp areas in the present trial. It is likely then that the gradient of dung return away from campsites will be more gradual where topographical changes are not abrupt. Where such changes do occur,

surface steepness alone becomes the major influence affecting the level of dung return.

3.3.4.2 Seasonal uptake and return of P

The seasonal net P balances comprising the annual totals are shown in Table 3.20. In general, the greatest proportion of the net TP losses from slopes occurred in spring and summer. The net TP surplus on campsites accumulated largely during the same period but was also high in autumn.

The relatively wide confidence limits of the estimates of net P balance for the slope sites in autumn and for all sites in winter preclude any detailed interpretations but it would appear that the net balance was small at those times.

The above seasonal P balances are based on the assumption that P uptake from the soil and also P return to the soil via litter and dung occur completely within each season. This would not strictly apply in the field but was adopted as a first approximation in the absence of information relating to the rates of P release and mineralization from litter and dung residues in this situation. If as an alternative approximation, however, it is assumed that there is a 3-month delay in P release from organic residues (e.g., P from litter and dung accumulated in spring is released to the soil during summer) then the estimated seasonal net P balances alter considerably (Table 3.21). On campsites there is a net P loss in spring, and autumn becomes the season of greatest net P surplus. On 25° slopes net P losses occur in spring and summer but a P surplus occurs in autumn and winter. The net P balances on the 45° slopes were little affected by the modified calculation.

It cannot presently be stated which approximation (i.e., results in

Table 3.20 Seasonal total P net balance
on each stratum (kg ha⁻¹)

Season	North aspect			South aspect		
	Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
Spring	+ 6.2	- 14.3	- 8.4	+ 34.6	- 3.9	- 6.2
S.E.	14.3	3.3	1.2	17.8	3.5	1.9
Summer	+ 28.5	- 3.1	- 4.1	+ 42.9	- 4.1	- 3.5
S.E.	14.9	2.8	1.0	20.2	2.8	2.1
Autumn	+ 22.1	- 1.4	- 1.2	+ 35.9	- 1.0	- 3.4
S.E.	13.6	1.6	1.1	18.3	1.9	1.1
Winter	+ 3.8	- 0.7	- 1.6	+ 6.4	- 1.0	- 0.7
S.E.	7.3	1.3	1.0	5.3	1.3	0.7

Table 3.21 Seasonal total P net balance on each stratum assuming a 3-month delay in availability of P from litter and dung (kg ha^{-1})

Season	North aspect			South aspect		
	Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
Spring	- 12.5	- 17.1	- 9.0	- 11.5	- 11.2	- 7.1
Summer	+ 20.7	- 5.3	- 4.5	+ 40.3	- 1.8	- 4.2
Autumn	+ 33.3	+ 2.5	- 1.1	+ 53.0	+ 2.5	- 2.1
Winter	+ 19.3	+ 0.4	- 0.7	+ 38.0	+ 0.5	- 0.4

Table 3.20 or 3.21) more closely resembles the field situation. Both approaches show that spring is the season of greatest net P loss from slopes, or smallest net P gain to campsites, and that any depletion of soil P would predominantly occur during this season.

3.3.4.3 Dung P and litter P relationships

The seasonal and annual TP returns in dung declined markedly from campsites to 25° slopes to 45° slopes (Table 3.14). Because litter P was much more evenly distributed over all sites (Table 3.18) it was of relatively greater importance as a P return pathway to the steeper slopes. Hence, TP returned in litter was higher than in dung on the north aspect 45° slopes in all seasons and also on the south aspect 45° slopes in autumn and winter.

In any pasture situation it would be expected that as grazing pressure and animal intake increased, so the level of P return via dung would similarly increase; conversely, the pasture which remained to be returned to the soil via litter would decrease. This was demonstrated by Rhoades et al. (1964) who measured a decrease in litter dry matter from 952 to 274g m⁻² as grazing increased from nil to heavy pressure. An examination of dung and litter accumulation on the same plots within any one season showed no such definite relationship. It must be concluded, therefore, that at the high overall level of grazing pressure applied, the variation in within-season dung accumulation was also affected by other factors. This could include pasture species which tend to trap more dung or produce more litter than others, or plot location relative to sites upslope which may tend to contribute any dung dropped or dislodged by grazing stock.

Similarly, the between-season differences in litter P accumulation were not significantly related to the levels of dung P at those times. On all areas, however, both dung P and litter P tended to be high in summer and low

in winter due to the different levels of pasture growth. The more independent variations which occurred in other seasons, on the other hand, precluded the existence of any significant relationships throughout the year. If the seasonal dung P and litter P data are expressed as a percentage of the TP uptake by pasture in each season, a more valid between-season comparison can be made without the over-riding effect of pasture production level influencing the direction of the relationship.

The modified data (Fig. 3.3) indicate positive, but not significant, relationships between dung P and litter P levels on both campsites (Fig. 3.3A) and 45° slopes (Fig. 3.3C), and a negative relationship on the 25° slopes (Fig. 3.3B).

Any positive relationship between dung P and litter P accumulation on campsites would most likely be due to the effect of pasture fouling by dung resulting in pasture rejection by stock (Norman and Green, 1958; Marsh and Campling, 1970). The slight positive association on the 45° slopes was possibly due to physical entrapment of dung by pasture and litter on these steep areas. More dung would be held when pasture was long, and litter also relatively abundant, than when growth was slower and grazed more closely. On this stratum, therefore, any such relationship existing at a high pasture utilization level is likely to be an effect of litter on dung accumulation, i.e., the reverse of that on the campsites.

On 25° slopes the proportional contribution from litter (y) decreased as that from dung (x) increased. The analysis using all data ($y = 21.2 - 0.12x$; $r = 0.163$) was strongly affected by the isolated data point (ringed in Fig. 3.3B) showing both proportionately low dung P and low litter P return. These values were measured on the north aspect in spring and because litter was low on all sites at that time, it appears that dung P on this site was underestimated, perhaps partly because of inadequate replication of dung collection plots in early spring (Section 3.2.5.1).

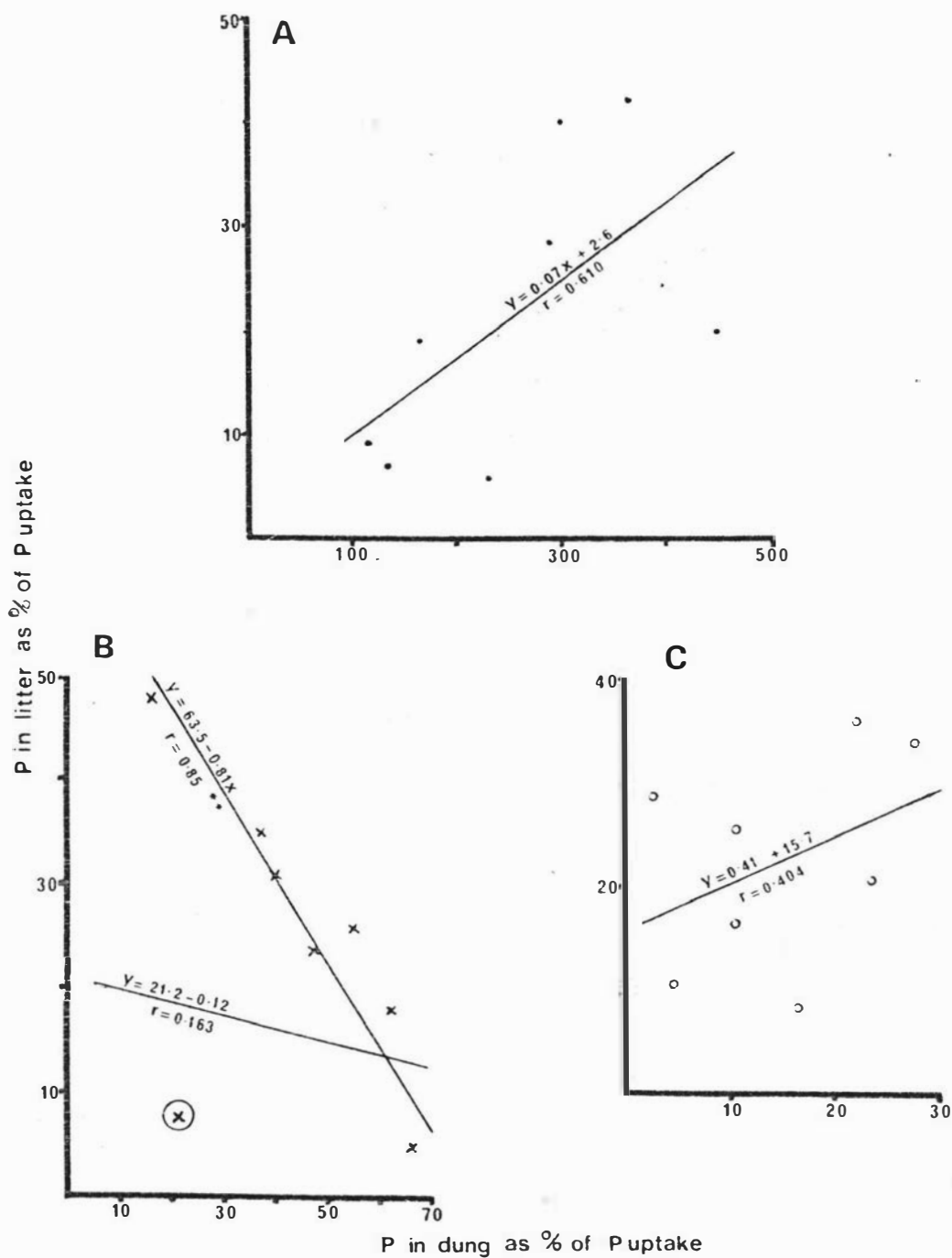


FIGURE 3.3 Relationship between total P return in litter and total P return in dung in each season (as % of P uptake by pasture); \cdot = campsites, \times = 25° slopes, and \circ = 45° slopes.

The associated data point representing the south aspect in spring (showing $y = 5\%$ and $x = 66\%$ of P uptake) was apparently not affected by inadequate replication.

A second analysis excluding this data showed a strong negative relationship between proportional litter P (y) and dung P (x) return for all other results ($y = 63.5 - 0.81x$; $r = 0.850^{**}$). This indicates that on 25° slopes the return of dung P was not greatly modified by camping behaviour at one extreme as on the campsites, or by surface steepness at the other, as on 45° slopes, but was more closely related to normal grazing effects. The emergence of this relationship from the modified data, compared with the relatively unchanged relationships on the camp and 45° sites, suggests this to be a real effect because other seasonal factors were also similar on these other sites. The same relationship was not expected on examination of the within season results for 25° slopes. The narrow range in litter accumulation, due to high overall grazing pressure, combined with the relative variability in dung return would have obscured any existing within-season relationship. This overall relationship emerged only by comparing the wider range in dung:litter ratios existing over the year.

3.3.4.4 Dung P return and net P balance relationships

The relationship between dung P return and the net seasonal P balance (Table 3.20) for each stratum is shown in Fig. 3.4. As discussed previously, there is a strong correlation between net P surplus (y) and total dung P return (x) on campsites in each season ($y = 0.78x - 4.3$; $r = 0.896^{**}$).

A similar analysis of results from the 25° and 45° slopes, however, showed that the seasons of greatest dung P accumulation were also times of greatest net P loss from these areas. Although the data was of a very clumped nature and therefore of limited value the results do demonstrate the effect of topography on the relationship. Data from the 25° slopes were

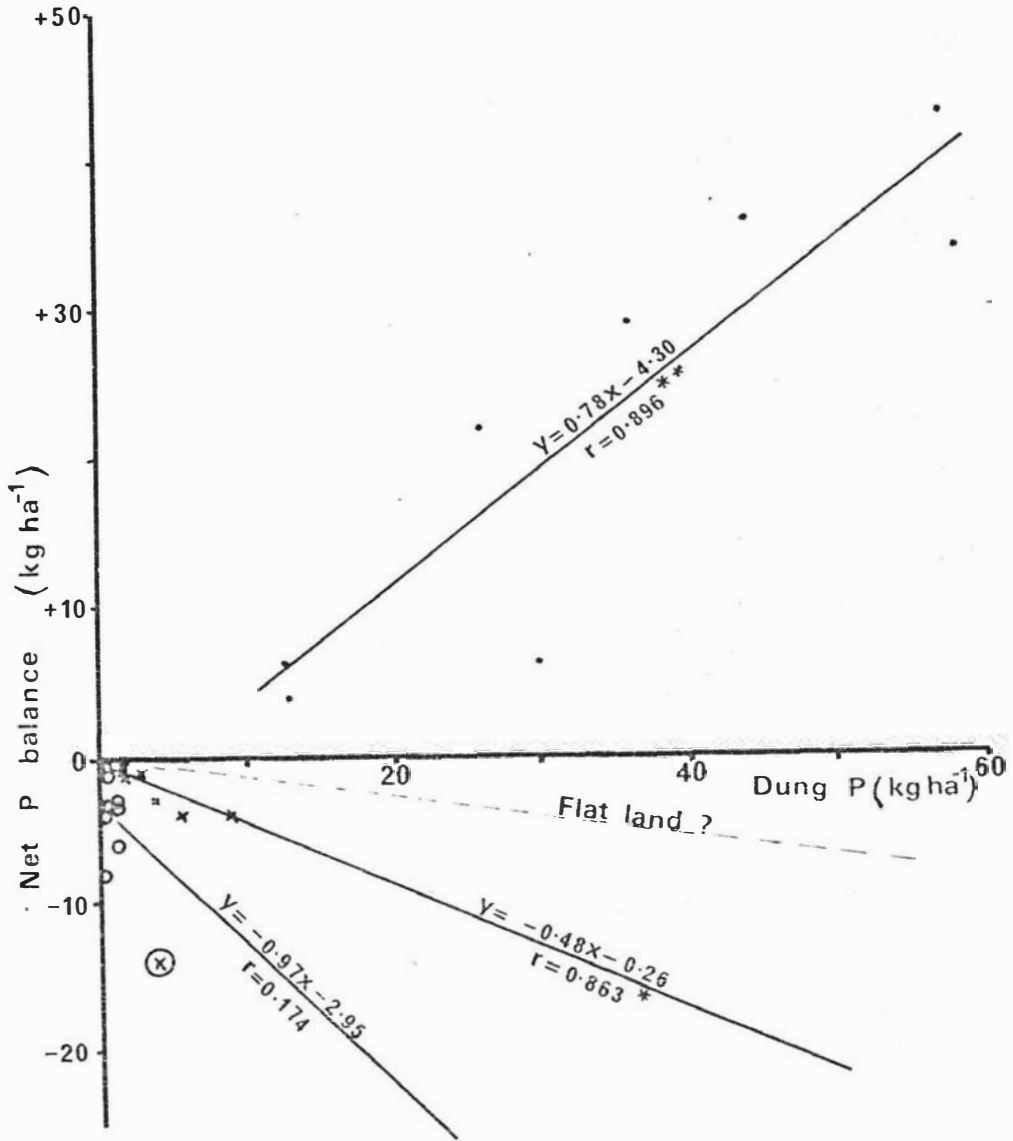


FIGURE 3.4 Relationship between net total P balance and total P return in dung in each season (kg ha⁻¹);
 • = campsites, x = 25° slopes, and o = 45° slopes.

analyzed both with ($y = -0.51x - 1.67$; $r = 0.285$) and also without the ringed data point measured on the north aspect in spring ($y = -0.48x - 0.26$; $r = 0.863^*$). The latter analysis showed that changes in dung P return during the year account for a large proportion of the variation in net P loss from 25° slopes, at least on all but the north aspect in spring. As discussed above, the amount of dung returned to the north aspect in spring may have been under-estimated. The low value still serves to demonstrate the marked effect of dung P return on the net P loss from these strata.

The seasons of greatest net P loss from 25° slopes were spring and summer when pasture P uptake was highest. Dung P return was also highest at these times, but as is evident from Fig. 3.4 associated transfer effects were even more marked, resulting in higher net P loss than in seasons of slower pasture growth. The same relationship would apply in comparing areas of the same slope but differing pasture production at any one time. If similar data had been collected from flat land sites the dung P:net P loss line would lie somewhere below zero, as suggested by the dotted line in Fig. 3.4. This is so because total P loss in animal products and by transfer to camps and yards increases as the total P intake of the animal increases. The greater steepness of the dung P: net P loss relationship for 25° slope strata illustrates the modifying effect of topography.

The topographical effect was at the most extreme on the 45° slopes in that dung P was always very low and so showed no strong relationship with net P loss (i.e., $y = 0.97x - 2.95$; $r = 0.174$) which was determined largely by other factors.

While a comparison of actual data illustrates the relationship between dung return and net P loss in different seasons it also tends to be dominated by seasons of both very high and very low pasture growth. For this reason the regressions of net P balance and P in dung were derived as

a percentage of total P uptake (Fig. 3.5).

As expected, this shows that the relative surplus P on campsites is almost completely dependent on the P in dung deposited there (Fig. 3.5A). If entirely dependent, the regression line would have crossed the dung P axis (x) at 100%.

On 25° slopes the proportional net P loss (y) tended to decrease as the contribution from dung (x) increased (Fig. 3.5B). As in Fig. 3.3B, the data point for the spring north aspect appeared isolated (ringed in Fig. 3.5B) in relation to the remaining points and therefore the non-significant relationship derived by omitting this point ($y = 0.19x - 36.5$; $r = 0.370$) may be more valid than that using all data ($y = 89x - 74.2$; $r = 0.776^*$).

The modified regression shows that even though dung provided the major P return pathway on 25° slopes (Fig. 3.2) and had a substantial P content in relation to pasture P uptake (i.e., 37.1 to 66.3%), the proportional net P loss was not affected by changes in the relative dung P return. This reflects to some extent the strong compensating inverse relationship between proportional dung and litter P accumulation (Fig. 3.3B) but perhaps also the more powerful transfer effect by stock away from these sites.

The proportional net loss from 45° slopes tended to decrease as the contribution from dung increased (Fig. 3.5C). This was to some extent probably due to an associated increase in P return from litter (Fig. 3.3C) and therefore any decrease in net P loss was related as much to an increased contribution from litter as it was to higher dung P return.

It would be expected that at a very low grazing pressure on these steep sites, litter P would be higher and, because of negligible stock presence, dung P lower, i.e., the nature of the dung:litter relationship would change to become similar to that found for 25° slopes. It is obvious then that over a range of pasture utilization levels on 45° slopes, P return

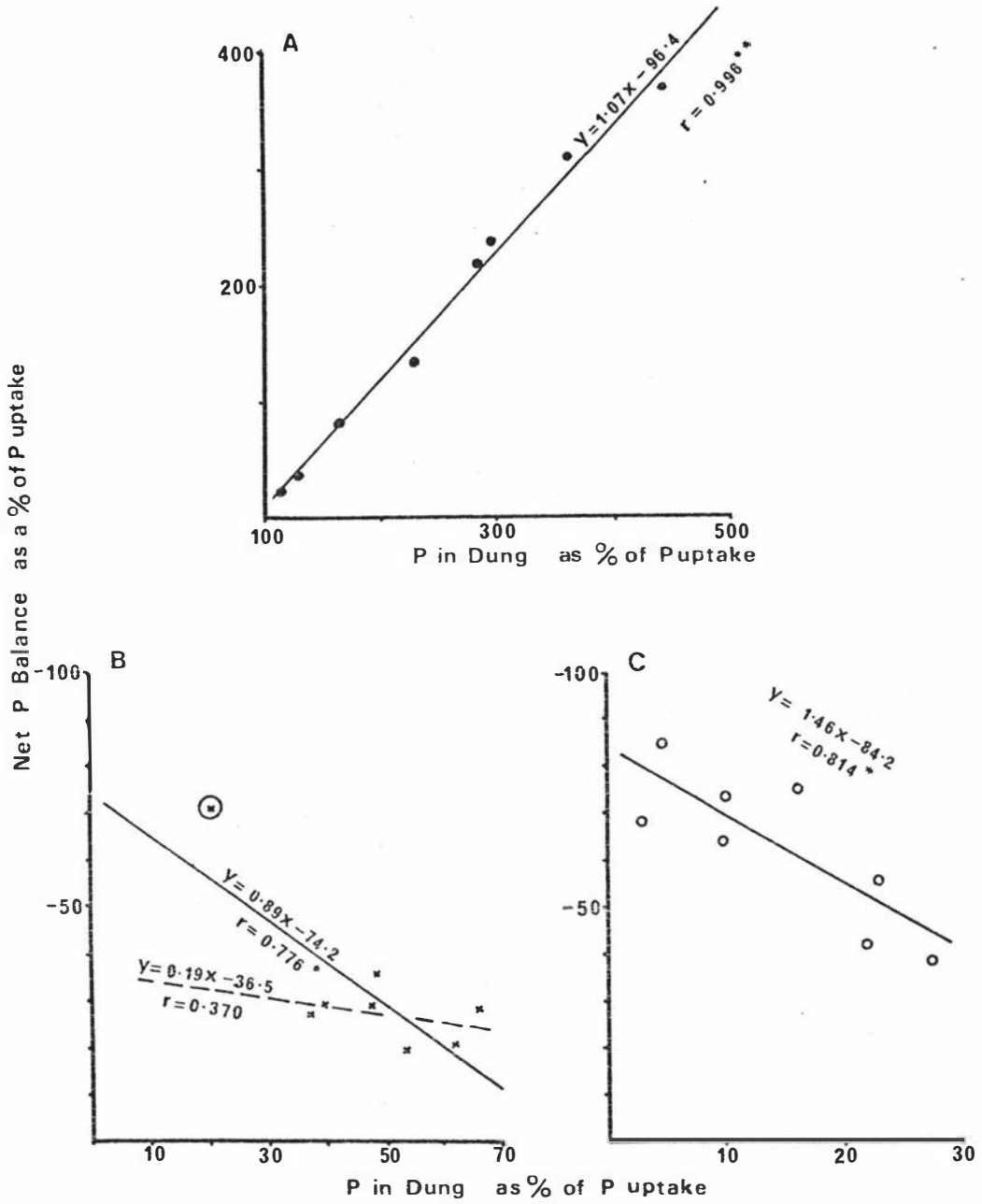


FIGURE 3.5 Relationship between net total P balance and total P return in dung in each season (as % of total P uptake by pasture); * = campsites, x = 25° slopes, o = 45° slopes.

via litter will have the closest relationship with net P loss. Conversely, dung P will always tend to be of little significance because of surface steepness, regardless of grazing pressure.

The regression of net P loss (y) with litter P (x) for the 45° slopes, expressed as percentages of pasture uptake, was $y = -93.1 + 1.35x$ with a correlation coefficient r of 0.860**, i.e., very similar to that derived for dung P under the same conditions.

3.3.5 Soil phosphorus

3.3.5.1 Total phosphorus

Topsoil (0-3cm) TP levels were high on campsites (Fig. 3.6), lower on 25° slopes (Fig. 3.7), and even lower on 45° slopes (Fig. 3.8). On all strata, TP levels decreased sharply with increased soil depth so that the TP content of 0-3cm depth soil was at least double that of soil at 3-7cm depth and about four times higher than the P content of soil at 7-15cm depth. Soil TP at 15-30 and 30-45cm depths was measured at only the first and final sampling dates. These results showed a further decline in soil TP content with depth (Appendix V). The TP present in the 0-3cm depth soil of each stratum represented a significant proportion of the total soil P to 45cm depth. By relating TP content to depth of soil measured, it can be shown that the 0-3cm depth contained approximately 26%, 34%, and 29% of the total soil P in the campsite, 25° slope, and 45° slope strata, respectively. This represents a relatively high proportion of total P concentrated in only a very shallow layer of surface soil.

The measured soil TP levels showed some marked apparent fluctuations during the year. The amplitude of these changes was greatest in the 0-3cm depth soil than at greater depths and more extreme on the campsite than on other strata, i.e., the degree of fluctuation was proportional to TP status.

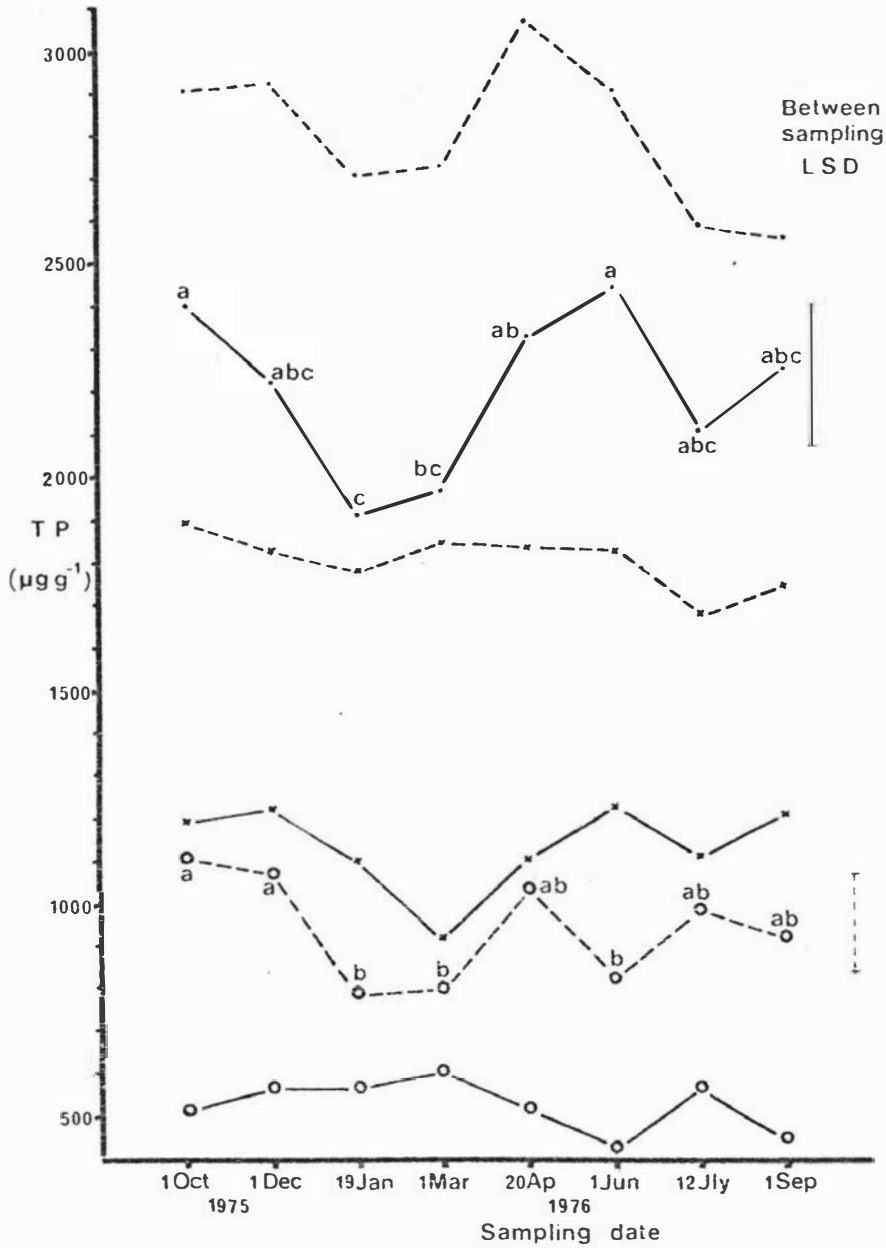


FIGURE 3.6 Soil total P content ($\mu\text{g g}^{-1}$) on campsites; solid lines = north aspect and broken lines = south aspect; \cdot = 0-3cm, \times = 3-7cm and o = 7-15cm soil depth. LSD = Least Significant Difference at 5% level of probability. Sampling dates with common letters have values not significantly different at the 5% probability level.

LSD levels not shown unless differences are significant.

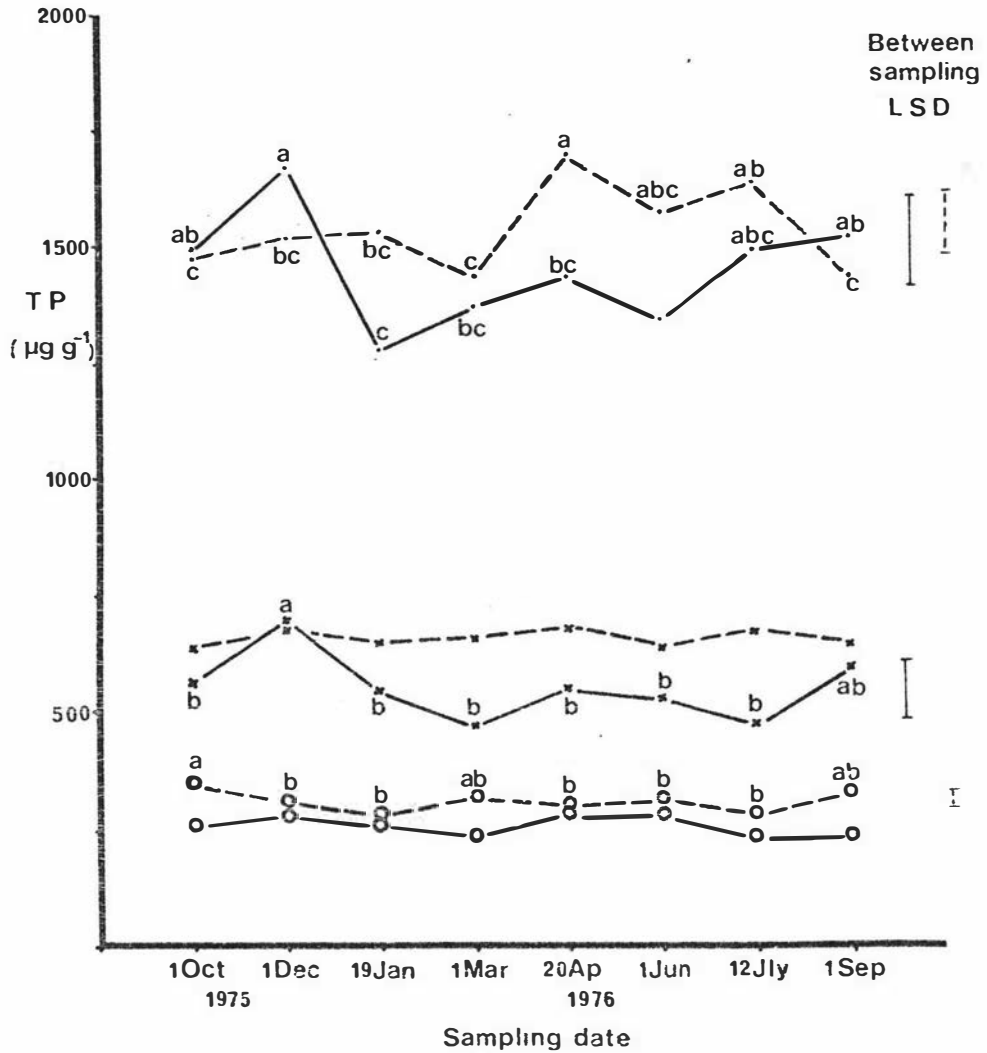


FIGURE 3.7 Soil total P content ($\mu\text{g g}^{-1}$) on 25° slopes; solid lines = north aspect and broken lines = south aspect; \cdot = 0-3cm, \times = 3-7cm, and \circ = 7-15cm soil depth.

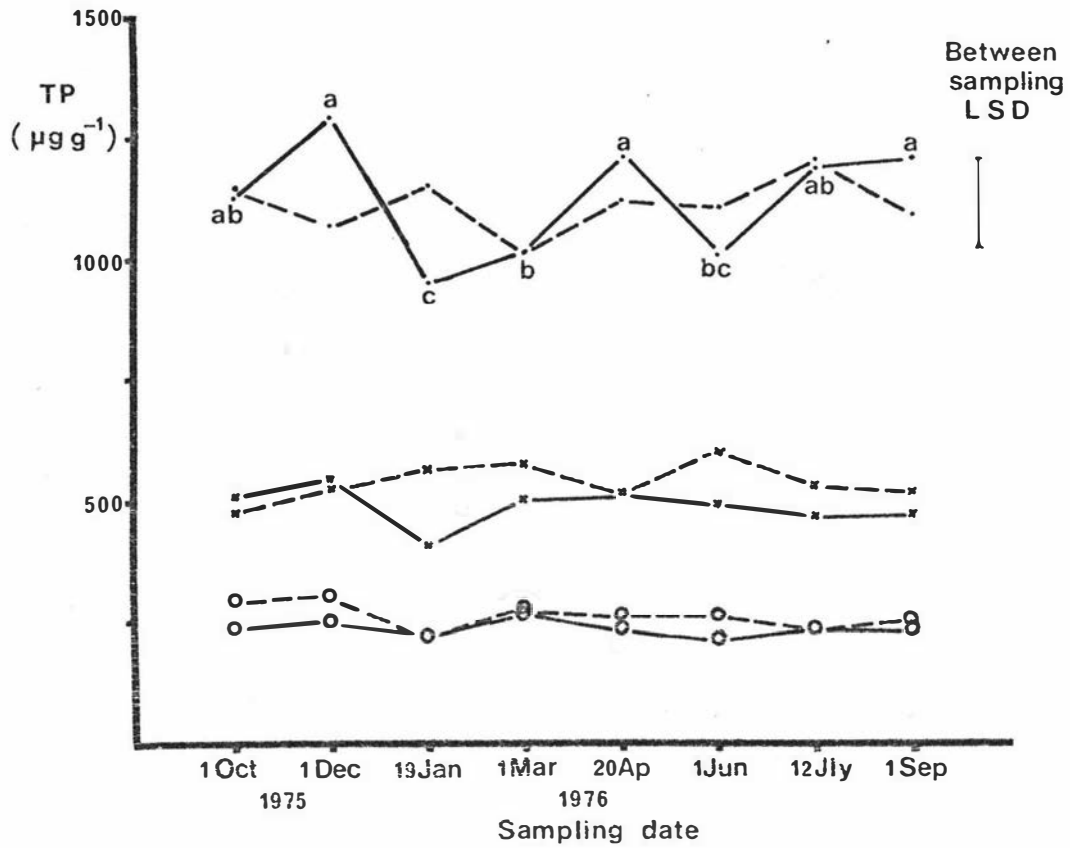


FIGURE 3.8 Soil total P content ($\mu\text{g g}^{-1}$) on 45° slopes; solid lines = north aspect and broken lines = south aspect; \cdot = 0-3cm, \times = 3-7cm, and \circ = 7-15cm soil depth.

The TP values in the 0-3cm depth soil from the north aspect campsite in particular showed a marked decline during spring and summer and a subsequent recovery in autumn and early winter. The extent of these changes, however, were far greater than could be attributed to net P losses which may have occurred from campsites in spring (Table 3.21), or to the combined effects of the added fertilizer (approximately 25 kg P ha⁻¹ on February 10) and a net P surplus in autumn (Tables 3.20 and 3.21). For example a TP value of 2500µg P g⁻¹ in campsite topsoil represents approximately 600 kg P ha⁻¹ in the 0-3cm depth soil. The high TP content and associated high LSD values would have obscured any real changes that may have occurred due to net P loss, or accumulation, or to topdressing.

The large, non-significant variation in measured TP levels on campsites was not due to differences in soil variability on different sampling occasions. Checks on the variance of samples collected at each date showed that they were not from significantly different populations. The variability in results must therefore be considered in relation to possible variation in other soil properties. It is possible that some of the variability in TP levels may be attributed to variable incomplete recovery of P by the ignition method used. It was shown in Section 5.3.2.1 that the ignition method recovered significantly less TP in this soil than that recovered by the carbonate fusion method (Syers et al., 1968). The ignition method total P values were higher as a proportion of carbonate fusion TP, where the organic matter content of soil was also higher. The relationship between 'ignition' TP and organic matter content (determined on 4 occasions as shown in Table 3.22) was therefore determined. This showed that variation in soil organic matter content between samplings accounted for approximately 30% of the variability in 'ignition' TP content of the 0-3cm campsite soil (i.e., north campsite $r = 0.537^*$; south

Table 3.22 Organic matter content of soil
on each stratum at four sampling dates (% by wt)

Sampling date	Stratum	North aspect			South aspect		
		0-3 (cm)	3-7 (cm)	7-15 (cm)	0-3 (cm)	3-7 (cm)	7-15 (cm)
1.3.76	Campsites	27.2	16.7	13.2	28.4	22.7	13.3
	25° slopes	25.0	15.1	12.8	20.4	16.6	12.6
	45° slopes	17.8	14.0	12.7	15.8	14.1	10.8
1.6.76	Campsites	31.3	19.1	13.7	29.2	21.7	15.0
	25° slopes	24.7	15.3	11.0	22.2	18.2	13.4
	45° slopes	17.8	13.7	9.1	17.8	13.3	11.0
12.7.76	Campsites	27.0	17.9	14.2	27.1	21.7	16.1
	25° slopes	25.5	15.3	12.9	23.4	16.7	12.8
	45° slopes	18.7	13.9	12.3	18.4	14.2	11.1
1.9.76	Campsites	28.4	17.2	12.6	25.9	19.1	12.6
	25° slopes	26.3	15.6	11.3	19.7	13.2	11.4
	45° slopes	19.5	13.5	10.4	14.9	11.3	9.0

campsite $r = 0.545^*$). The residual soil TP variability remains unexplained.

The 0-3cm TP values on 25° and 45° slopes showed a decline in early summer and a subsequent irregular but gradual increase during the remainder of the year. The same changes were not evident on the south aspect. The supply of P from added fertilizer or estimated loss of P by transfer could represent only a small part of the changes in TP that occurred in each season. The greater proportion of the fluctuations must, as in the campsite soil, be attributable to other factors. Variable organic matter content of the soil may again be responsible for some of this variability.

3.3.5.2 Soil DIP

The amounts of DIP also fluctuated considerably throughout the year, particularly in the 0-3cm depth on each stratum. This variation may have been associated to a large extent with the factors causing variation in TP and therefore DIP levels were expressed as a percentage of TP. By this means any DIP variation unrelated to TP variation could be examined.

Results for the campsites (Fig. 3.9A), 25° slopes (Fig. 3.9B), and 45° slopes (Fig. 3.9C) showed that on each stratum, at each soil depth, DIP was a relatively constant proportion of TP throughout the year. The soil DIP values were higher on the campsites, both as a proportion of TP and in quantity, than on either 25° or 45° slopes, therefore demonstrating that as soil TP content rises the proportion of DIP also increases. Consequently, the DIP in campsite soils did not decline as sharply with depth as on the slopes where the DIP content of 3-7cm depth samples, as a percentage of TP, was similar to that in 7-15cm samples. The proportion was also similar at 15-30 and 30-45cm depths on the two occasions measured (Appendix V).

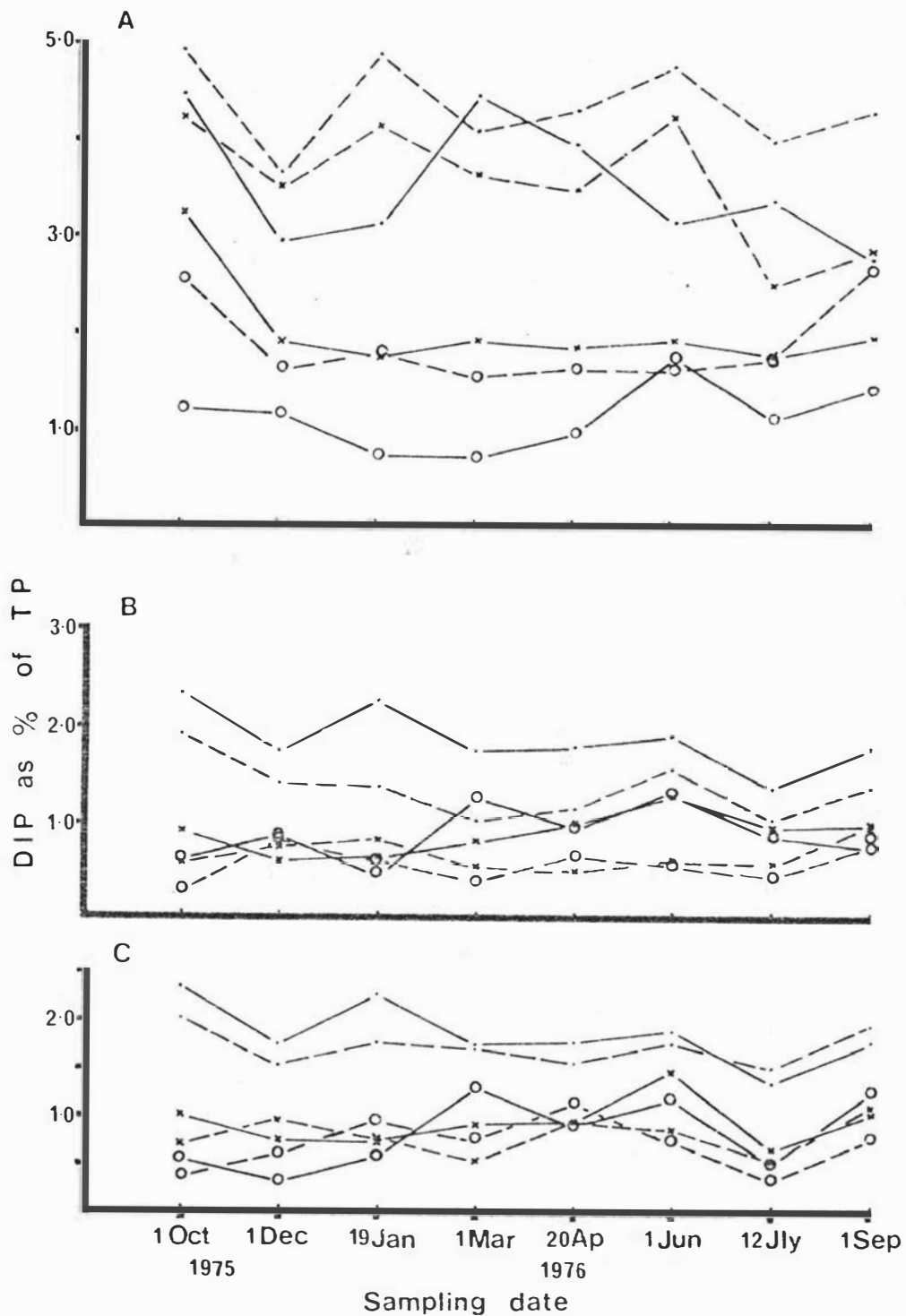


FIGURE 3.9 Soil DIP (as % of TP); solid lines = north aspect and broken lines = south aspect; \cdot = 0-3cm, \times = 3-7cm, and \circ = 7-15 cm soil depth. A = campsites, B = 25 $^{\circ}$ slopes, and C = 45 $^{\circ}$ slopes.

The higher soil DIP levels on the campsites than on the slopes must be attributed largely to P release from the large accumulation of DIP derived from dung on these areas. Whereas a significant proportion of the TP in dung would have been readily water-extractable (Table 3.13), as defined by the laboratory procedure used, the actual amounts and rates of release of P from dung in the field would have greatly been modified by the physical form of the material (Bromfield and Jones, 1961), the density of the dung pellets (Table 3.9), and also by seasonal variations in temperature (Floate, 1970c) and moisture content of the material (Floate, 1970d). Because the various effects of these and other factors are unknown, the total mineralization and release of P from dung over a year cannot be determined. It would appear from the relatively constant proportion of soil DIP throughout the year, and as demonstrated in Section 5.3.3.1. that P from dung and litter was rapidly converted to water-insoluble forms in the soil. The extent of such conversion may be better appreciated when it is considered that the annual net P surplus on campsites was equivalent to approximately 300% and 450% of the 0-3cm soil depth DIP content on north and south aspects, respectively.

If relatively large annual inputs of P to campsites were not reflected in increased DIP levels it would be expected that smaller net transfer losses of P from slopes would also be undetected. The estimated net annual TP loss from both 25° and 45° slopes (i.e., from 10.0 to 19.5 kg P ha⁻¹) however, was equivalent to between approximately 200 and 300% of the measured DIP pool to 3-cm soil depth. If related to a more realistic plant P uptake depth, e.g., 7cm, these changes would represent a lower proportion of soil DIP status although, as indicated by relative root activity measurements (Section 4), the greatest uptake would occur from the 0-3cm soil depth. Because soil DIP is considered to be plant-available in

the very short term (Ryden and Syers, 1977) the rates of P release into, and plant removal from, the soil DIP pool must have been sufficiently similar to prevent marked changes in P status occurring.

3.3.5.3 Soil DOP

The soil DOP data were also expressed as a percentage of TP at each sampling date (Table 3.23). Results were more variable than for DIP, both within and between sampling depths at any one time, and also between sampling dates throughout the year. In general, the results were similar on all strata and at all depths; i.e., DOP as a proportion of TP was relatively uniform. Actual DOP levels were higher and more variable in 0-3cm soil samples than at greater depths in all strata.

On campsites, DIP generally comprised the greater part of TDP at all sampling depths throughout the year. On 25° and 45° slopes, however, DIP was predominant only in the 0-3cm soil layer. At 3-7 and 7-15cm depths, the proportion of DOP appeared to be higher than that of DIP in spring and early summer but at all other times they were similar in amount. On October 1, 1975 DOP on 25° and 45° slopes was a relatively high proportion of TP at 15-30 and 30-45cm depths. Values were similar at both depths and on all strata on September 1, 1976 (Appendix V).

3.3.5.4 Bicarbonate-extractable P

Sodium bicarbonate-extractable P (modified Olsen method) was determined at each mid-season only. There were no statistically significant changes in Olsen P levels over the 9-month period for campsites and 45° slopes. For 25° slopes, the north aspect 7-15cm depth showed a significant increase ($P \leq 0.05$) at the January sampling, as did the south aspect 0-3cm sample in April ($P \leq 0.05$). Both values decreased again at the subsequent sampling.

Table 3.23 Water-extractable organic P content of soil
on each stratum (as % of TP)

Sampling date	Stratum	North aspect			South aspect		
		0-3 (cm)	3-7 (cm)	7-15 (cm)	0-3 (cm)	3-7 (cm)	7-15 (cm)
1.10.75	Campsites	1.4	1.7	1.1	1.3	1.5	0.5
	25° slopes	2.7	2.0	2.3	1.3	1.1	1.6
	45° slopes	2.1	1.1	2.0	1.2	1.2	1.7
1.12.75	Campsites	1.4	0.6	0.6	2.2	0.9	0.7
	25° slopes	1.4	1.1	0.8	1.7	1.5	1.3
	45° slopes	1.2	1.5	1.1	1.6	1.3	1.3
19.1.76	Campsites	1.0	0.8	1.0	1.1	0.9	1.0
	25° slopes	1.1	1.8	1.9	1.2	1.2	2.1
	45° slopes	1.0	1.4	1.7	1.1	1.3	1.9
1.3.76	Campsites	0.4	0.5	0.4	0.5	0.6	0.6
	25° slopes	1.1	1.1	0.5	0.8	0.8	0.9
	45° slopes	1.1	0.7	0.5	0.6	0.8	0.6
20.4.76	Campsites	0.6	0.7	0.8	1.7	0.6	0.6
	25° slopes	0.9	0.9	0.9	0.9	0.8	1.3
	45° slopes	0.7	0.9	1.1	0.9	0.6	0.8
1.6.76	Campsites	1.2	0.5	0.4	1.4	0.6	0.4
	25° slopes	1.2	0.5	0.8	1.2	0.9	0.8
	45° slopes	0.8	0.3	0.7	1.0	0.7	0.8
12.7.76	Campsites	0.4	0.9	0.6	0.5	0.8	0.5
	25° slopes	1.2	0.7	0.9	0.9	0.9	0.8
	45° slopes	1.1	1.2	1.1	0.9	1.1	0.9
1.9.76	Campsites	1.2	0.6	0.5	0.7	0.6	0.5
	25° slopes	1.0	0.9	1.3	1.0	0.7	0.8
	45° slopes	0.9	0.7	1.1	1.0	0.8	0.7

The results expressed as a percentage of total TP are presented in Figure 3.10. The proportion of Olsen P was similar at all depths on each campsite (Fig. 3.10A) but was lower and decreased more with depth on both 25° slopes (Fig. 3.10B) and 45° slopes (Fig. 3.10C).

Expression of the estimated annual net TP surplus on campsites in terms of Olsen P values, showed that on the north aspect the estimated P surplus of 60.7kg was equivalent to approximately 110% of the 0-3cm Olsen P value. On the south aspect the estimated surplus of 119.8kg P ha⁻¹ was equivalent to 160% of the Olsen P value. Together with the P applied as fertilizer (25kg P ha⁻¹) this represented a large P input to these areas. No increase in Olsen P, however, was recorded ^{on campsites} during the year. As shown in laboratory studies (Section 5.3.3.1.) approximately 2/3 of applied P may be lost from an Olsen-extractable form within a week of addition to these soils. This would reduce the expected increase in Olsen P values to a moderate level. Halm et al. (1972) noted fluctuations in Olsen organic P levels which tended to compensate for changes in Olsen inorganic P. It is possible that such changes, which may be partly related to variation in rainfall and temperature (Jessop et al., 1977), could occur following addition of inorganic P and thus further modify the effects of such additions. The above effects may explain to some extent the apparently stable Olsen soil P levels on campsites throughout the year. Replicate variability at each sampling date however, would have largely obscured changes of the order expected.

The above discussion similarly applies to the use of Olsen P analysis to detect the smaller apparent transfer losses of P from slope strata, and, particularly during spring when losses predominantly occur.

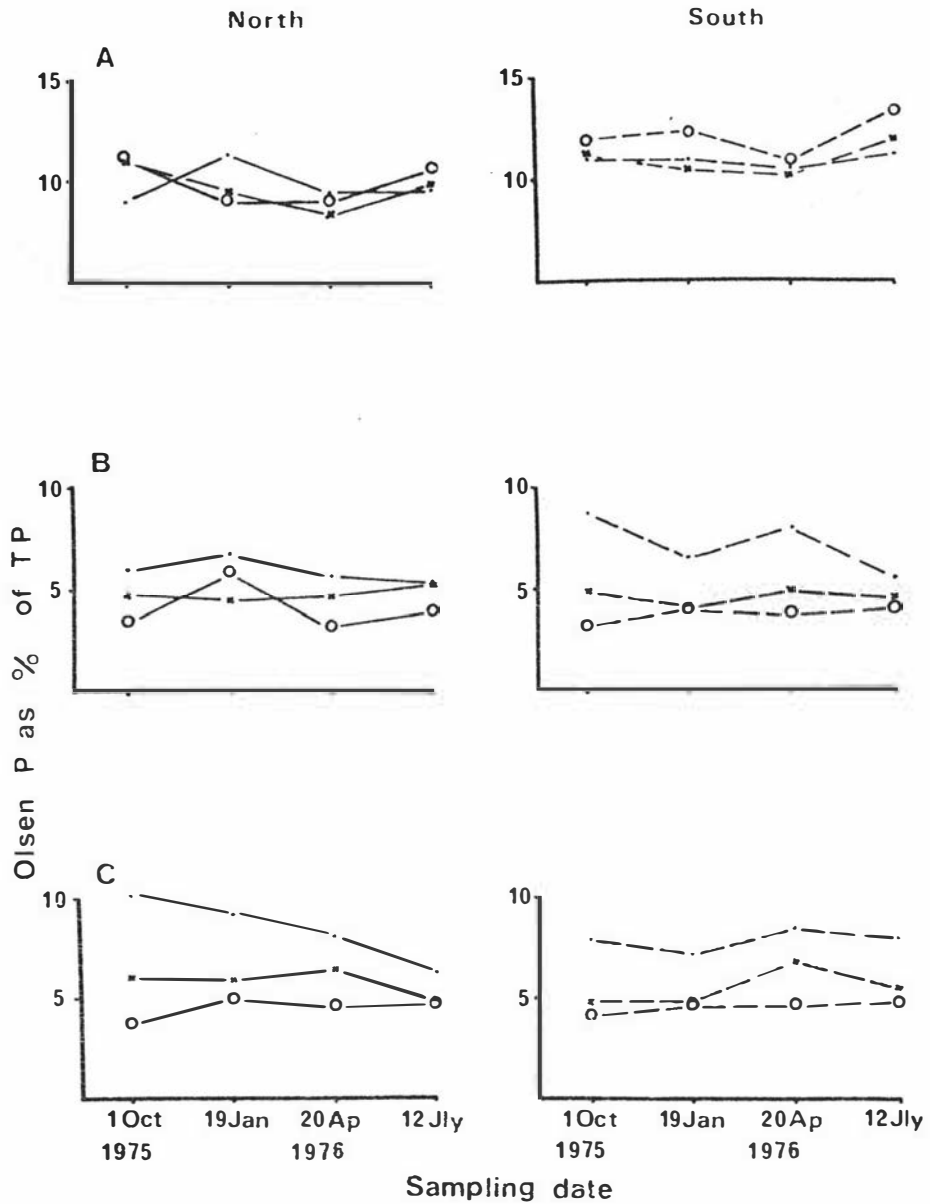


FIGURE 3.10 Olsen P (as % of TP); solid lines = north aspect and broken lines = south aspect; · = 0.3cm, x = 3-7cm, and o = 7-15cm soil depth. A = campsites, B = 25° slopes, and C = 45° slopes.

3.4 General Discussion

It has widely been recognised (During, 1972) that in many hill country situations pasture improvement by topdressing can be a relatively slow process. The significant transfer of P from slopes by grazing animals measured in this study demonstrates why this can be so. The three strata selected for study demonstrate well how topography affected both the level and relative importance of dung and litter as a source of plant-available P and consequently the net P balance on each stratum. In campsites the regular supply of P and other nutrients from dung and associated urine (Peterson et al., 1956b; Hilder, 1966) was more than sufficient for pasture needs, with the soil serving to a large extent, merely as the substrate on which this occurred. On moderately-steep (25°) slopes total P return in dung and litter was less than that required for annual pasture needs and therefore topdressing was necessary to avoid some depletion of soil P. On the steepest slopes (45°) only a small proportion of total P uptake was returned and the 'above-ground' P cycle was largely disrupted. Consequently, on this stratum the role of topdressing in maintaining soil P levels and therefore also plant P uptake, was vital and more important than in any other areas of the paddock.

The above conclusions are based on measured P uptake and return to the various strata over one year only. For such conclusions to be valid and relevant to longer periods the P cycle in each situation should be near equilibrium so that the various unmeasured rate factors operating between compartments of the cycle can be considered constant from year to year.

The extent to which this desirable condition existed in the situations studied must be considered both with regard to P uptake and P return to the soil by the above-ground components, including topdressing. If these tend to be relatively constant then the various soil compartment P

levels and associated rate factors should similarly tend toward an equilibrium.

Annual P uptake by plants is determined primarily by the pasture growth rate over a year. The first long-term pasture production measurements on North Island hill country were reported by Suckling (1954). Later results (1959, 1975) concluded a period of 21 years of measurements. These show that in southern North Island hill country, pasture production has varied considerably from year to year. For example, over the final 10 years from 1959 to 1969 annual dry matter production varied by up to 30% from the mean. Similar year to year variability was also measured at Whatawhata, (Ministry of Agriculture and Fisheries, unpublished trial results) in the period 1969-1975. A more detailed examination of the pasture growth data of Suckling (1975) revealed that variability in annual production was associated largely with summer and or autumn weather conditions. Minor carry-over effects into winter and spring, the seasons of more reliable rainfall, slightly modified the more stable growth patterns in those seasons also.

It follows then that with adequate soil P levels, pasture P uptake will be relatively constant from year to year during winter and spring but may vary considerably at other times. Because of the relatively high summer rainfall during the present trial, pasture production and P uptake from all sites over this period must be considered higher than average.

The situation in relation to P return is less well-defined. The immediate supply of P to plants over any period will be determined first by the 'available' P level in the soil. However the continued supply will be dependent on both the quantity of potentially-available P returned to the soil surface in litter, dung, and/or fertilizer, and also by the rate of P release from these materials.

The distribution patterns of pasture litter and dung on the soil surface differ dramatically. The very even spread of litter means that P is returned to the soil relatively close to the sites of uptake. The availability of P from litter therefore is governed largely by the prevailing levels of moisture and temperature which affect the rates of P release (Floate, 1970c, 1970d).

While moisture and temperature similarly affect P release from dung, the potential benefit is limited by the very clumped and biased pattern of distribution, as discussed in Section 3.3.2.2. The nature of dung distribution means that the efficiency of use of faecal P by plants will be affected critically by the rate of P release relative to plant uptake over any period. Excess water-soluble inorganic P from either litter or dung sources is likely to be rapidly lost from the plant-available soil pool as defined by isotopically-exchangeable and/or water-extractable P (Section 5). Therefore, a prolonged relatively slow release and mineralization of P from dung is desirable. The delayed plant-availability of P from dung following deposition on pasture (Watkin, 1957; During, 1972) is surprising considering the high level and proportion of inorganic P present in dung, especially that of high total P content, and also the considerable proportion of this which is readily water soluble (Section 3.3.2.3). Faecal P has generally been found to be of low immediate plant availability unless incorporated in soil (Gunary, 1968). Although Barrow (1975) explained this in terms of the P in dung being present as dicalcium phosphate, this conclusion is not supported by results from sequential water extraction experiments where large and declining proportions of inorganic P have been obtained in successive extracts (Bromfield, 1961; Floate, 1970a; Table 3.12).

The extent to which dung-soil contact occurs in grazed pasture will depend predominantly on the amount of trampling received. Such trampling

will be relatively intense on campsites but less so on 25° slopes. On 45° slopes it will be effectively non-existent as these sites are too steep for animal traffic and dung is returned to them only by stock grazing adjacent, less-steep sites upslope. From this consideration alone the rate of release of P from dung will decrease from campsites to 45° slopes. On these latter areas dung will only reach the soil following disintegration by rainfall or incorporation by organisms. The level of earthworm population in this situation could therefore have a significant effect on the plant-availability P derived from dung.

The amounts and forms of inorganic and organic P in dung, and to a large extent in litter, were at any time generally similar on both north and south aspects and therefore unlikely to contribute appreciably to any aspect differences in the rate of release or mineralization of P from these materials. It is likely, however, at the generally higher temperatures on the north aspect (Gillingham and Bell, 1977), that with adequate moisture, P mineralization and release will also be higher (Floate, 1970c; Biederbeck and Campbell, 1973; Ellis, 1974) from dung and litter material than occurs on the south aspect. As previously considered, however, the major factor limiting mineralization activity will be the rate of incorporation of organic residues into the mineral soil, especially on 45° slopes where the role of earthworms and other comminution organisms will be most important.

The high frequency and amount of P return relative to pasture uptake on campsites suggest that conditions on this strata are in a situation far removed from an equilibrium. The high and variable level of soil organic matter reflects the high dung return and associated organic P accumulation. Because soil P levels are presently high, pasture production and associated P uptake levels will not be affected appreciably by further net P gains. The rate of P return in dung is also likely to remain similar in the future

and therefore soil P levels, both inorganic and organic, should continue to slowly rise, especially at greater depths as has already occurred to a significant extent.

With similar variability in pasture production to that recorded by Suckling (1975), annual pasture P uptake from 25° and 45° slopes in the trial area could range from approximately 24 to 39 and 13 to 21 kg P ha⁻¹, respectively. It is likely that litter and dung P returns at any time would be in proportion to P uptake and so would be correspondingly lower at times of low pasture growth. At such times, however, grazing pressure is likely to be higher and less litter will accumulate. Similarly, because of lower overall stock numbers the dung return to each area would also be lower and the effective return intervals, as estimated in Table 3.8 would increase in direct proportion. As emphasized previously, the present trial measurements and estimates relate to a year of relatively high pasture growth and dung return and therefore dung return intervals must be increased by about 60% to represent periods of lowest annual production. The mean levels could be assumed to lie about mid-way in this range for each strata.

An important aim of the present study was to assess the efficiency of the P cycle with a view both to deriving an estimate of topdressing requirements and also to examine aspects of stock management which may help reduce fertilizer needs.

With respect to fertilizer requirements it can be concluded that probably one of the most significant practical findings from this aspect of the study is that the maintenance of soil P levels and pasture growth rates on slopes will at all times continue to be largely dependent on fertilizer inputs. Because fertilizer P is the predominant factor affecting the level of P uptake from 25° slopes it is probable that where the same topdressing

and grazing management has continued for several years, the above-ground components of the P cycle at least will be in relative equilibrium. Under intensive grazing the contributions from litter and dung to soil P on 45° slopes play an even smaller role than on 25° slopes and thus the importance of fertilizer P is even more pronounced on those areas. Blair et al. (1977) showed that at a given level of P transfer, P losses will be greater at higher available soil P levels. While actual transfer losses from slopes would therefore be lower if the soil in the present trial was of lower P status the maintenance of pasture growth on both 25° and 45° slope strata would continue to be highly fertilizer dependent.

It can be concluded that although soil P in campsites would appear unlikely to reach a steady-state condition under the present topdressing and management regimes, pasture P uptake from this strata will be unaffected by continued addition of P in dung and fertilizer. On slopes a stable fertilizer-induced soil P level could exist following several years of topdressing. Such a condition, however, would be highly fertilizer dependent and increasingly so on steeper slopes.

Results from the study also imply that the efficiency of the P cycle on each stratum can be modified by differing grazing management. Consideration of the factors influencing both pasture utilization and associated dung distribution suggests that if a predominantly mob-grazing system is used there are several likely benefits to be obtained relative to a set-stocking policy. The first is that higher overall pasture utilization can be obtained especially where stock carrying capacity is approaching optimum (McMeekan and Walshe, 1963; Campbell, 1966). Essentially, a mob-stocking method was used in the present trial, although stock numbers were in general less and grazing periods somewhat longer than in the method proposed by Smith and Dawson (1976). Very high pasture

utilization levels, however, were still achieved. The second benefit from mob grazing is that large numbers of stock grazing for short periods should reduce the tendency for nutrient transfer to limited areas of established stock camps. Because of the high stock numbers, additional camp areas have to be found. The second of these factors may have the most effect on dung return patterns, especially to less steep slopes. At a high grazing pressure, however, the dung return interval estimates for each stratum from either a mob-stocked or set-stocked grazing system should not be greatly different. The major advantage of a mob stocking system could be that the dung return times to the paddock as a whole will be more synchronized, i.e., the whole paddock will tend to receive dung in greater amounts on fewer occasions during a year. Such dung return will therefore coincide more with urine return to the same sites. The associated N and P return can be expected to have an interacting effect on pasture growth (Watkin, 1957; Wheeler, 1958; Simpson et al., 1974) for greater benefit than when return is more independent. It is probable then that at least part of the benefit claimed for mob stocking over set stocking is due to the more efficient utilization of P from dung, litter, and soil organic matter because of the paddock-wide, synchronized fertilizing effect and grazing of subsequent responses. Regardless of the system used on hill country, however, the rate and extent of dung and urine return to slopes as steep or steeper than 45° will always be very low.

Results from soil analysis during this study, when considered in relation to either annual plant P requirements or estimated annual net transfer of P on each stratum, suggest that in grazed, steep hill country such analysis is unable to detect equivalent changes in soil P status. Water-extractable inorganic P obviously represents a very labile P fraction which is rapidly replenished following any depletion as equilibrium between

solution and solid phases is restored. Olsen P, however, which represents a larger soil P 'pool', should be more stable and reflect more long-term effects of P addition or removal. The absence of such changes in either DIP or Olsen P levels on slope strata reflects the capacity of the non-extractable P fractions to buffer these effects. Changes in DIP or Olsen P, however, would, because of relatively high replicate variability, have had to exceed approximately 1/3 of DIP status and 1/5 to 1/3 of Olsen P status before they would have been statistically detected at the level of replication employed. Cole et al. (1977) concluded that operation of a P model was more sensitive to soil than to plant and decomposer parameters. Conversely, this means that relatively large changes can occur in plant and decomposer parameters before greatly affecting available soil P levels. This agrees with conclusions from the present study. In making similar observations relative to the effect of camping or cessation of topdressing on available soil P levels, Blair et al. (1977) concluded that the net effect was also very much a function of the level of organic matter and the rate of subsequent P mineralization.

In the present study the samples analyzed were from small, defined plots. It should be expected that results from routine sampling of large hill paddocks would show greater variability. In such situations, soil analysis may be expected to reflect only an approximate measure of soil P status, even within defined strata. Any real changes, due to moderate levels of topdressing or net losses by transfer would be detected only after relatively long time intervals, perhaps up to 5 years.

SECTION 4

UPTAKE ZONES FOR PHOSPHORUS BY PASTURE
ON DIFFERING STRATA WITHIN A HILL Paddock

4.1 Introduction

Soil contains the greatest amount of P involved in the P cycle at any one time. The very limited depth of distribution of a significant proportion of plant-available P, both on slopes and campsites (Section 3.3.5), suggests that the greater part of pasture P requirements on these strata is obtained from near the soil surface. This has been illustrated in other situations (Nye and Foster, 1960; O'Brien et al., 1967; Newbould et al., 1971; Halm et al., 1972; Jackman and Mouat, 1972; Maurya et al., 1973), for other nutrients, e.g., for S (Gregg et al., 1977) and K (Ozanne et al., 1964), and is also supported by measurements of root mass (Sprague, 1943; Troughton, 1957). While most of plant P is apparently obtained from a relatively shallow depth of soil, an evaluation of P uptake by deeper roots is necessary in order to identify the total effective soil depth involved in the P cycle on each stratum. Such measurements will also indicate the significance of soil drying and therefore the effect of season on plant P uptake, as demonstrated by Uyo (1974). Marked drying of surface soil is prevalent in late summer and autumn, particularly on north-facing aspects in New Zealand hill country.

Plants tend to overcome limited nutrient and moisture availability by a wide lateral spread of roots relative to the area occupied by the canopy. On flat-land, Troughton (1957) showed that root spread from some pasture species may extend to a distance of up to 30cm from the crown. In this way roots from one plant could cover an area of more than 0.25m^2 . Similar root spread on slopes could enable pasture plants on one stratum

to obtain nutrients from a nearby zone of higher status, e.g., where stock tracks cross steep slopes.

Root mass in any depth of soil does not necessarily represent the relative uptake of a nutrient from that zone because the activity per unit weight of root material tends to decline with increasing soil depth (Halm et al., 1972), probably because of the greater proportion of fine roots near the soil surface. Root weight alone, therefore, tends to underestimate P uptake from the topsoil and conversely over-estimate the uptake by deep roots.

The definition of nutrient uptake activity by roots using radioisotopes is now recognised as a reliable method. Recent refinements in field technique (Jacobs et al., 1970; Goh et al., 1977) have removed many of the objections relating to contamination and root disturbance during isotope placement associated with some earlier work (Weaver, 1926; Hall et al., 1953; Burton, 1957). Extreme care is required in the quantitative interpretation of results obtained by this method, which has a much wider application in supplying qualitative information. To be suitable for such experiments a radioisotope should exist as a carrier-free or high specific activity solution or powder which can readily be taken up by a plant but which will remain essentially immobile in the soil over the required uptake period. Isotopes of P are very suitable in these regards.

A trial was designed to measure P uptake in spring from varying depths by mixed pasture on campsites, 25° slopes, and 45° slopes. A separate study examined the availability to pasture of soil P at various depths, both upslope and downslope from stock tracks. The study was limited to a north aspect only because a larger trial could not have been accommodated with the time, facilities and labour available. The trial commenced on 13.9.76 and concluded on 12.10.76, a period in which near

maximum pasture growth rate and soil moisture levels occurred.

The study aimed at providing a comparative measurement of the relative P uptake activity distribution of mixed pasture roots both in relation to soil depth and also to lateral distance from a P source. No such previous measurements are known to have been made on hill slopes. The method of deriving relative root activity (RRA) was that of Jackman and Mouat (1972). Added ^{32}P was considered to rapidly equilibrate with soil ^{31}P . The ^{32}P activity in herbage was therefore proportional to the ^{32}P level added to soil and inversely related to the soil ^{31}P content at a given depth. Relative root activity at a certain depth was derived as a % of the sum of activities at all depths. Jackman and Mouat (1972) reported that corrections for variable plant P content did not essentially alter results. In this trial it was assumed that all pasture within each stratum was of similar P content.

4.2 Materials and Methods

At the conclusion of the trial described in Section 3 some plots used for pasture production measurement on campsites, 25° slopes, and 45° slopes in the north aspect paddock were selected as isotope placement sites. In addition, new sites on stock tracks adjacent to 45° slopes were located.

4.2.1 Treatments

On each of the campsites, 25° slopes, and 45° slopes four plots in each of five blocks were selected for separate placement of ^{32}P in the soil at $1\frac{1}{2}$, 5, 11, and 22 cm depths, respectively. These average depths represented the soil sampling zones of 0-3, 3-7, 7-15, and 15-30cm, respectively, used to measure soil P status in the previous trial (Section 3).

In addition six new sites per block were selected adjacent to stock tracks; three with 45° slopes immediately downslope of the track. In each group one site each was chosen for placement of ^{32}P at $1\frac{1}{2}$, 5, and 11 cm depths, in the track soil on either the inside edge or outside edge of the track, as related to upslope or downslope sites, respectively.

4.2.2 Isotope preparation

^{32}P as orthophosphate in dilute HCl and added to KH_2PO_4 (see below) was placed in the soil in gelatin capsules similar to those first used by Jacobs et al. (1970). A remote control method of filling and handling the capsules was devised (Plate 4.1) to accommodate the large number of capsules and relatively high specific activity of the total isotope involved in the trial.

A stainless steel "Ovijector" gun, as used for vaccinating animals, was clamped to a stand and the trigger extended by a 40-cm length of stiffened black plastic tubing. The intake hose fed from a piece of glass tubing through a hole in the bottom of an upturned aluminium can covering the beaker containing the isotope solution.

Each 2.0-ml volume capsule was placed in a short metal tube and a plastic cap with a small (3-mm diameter) hole in the centre and with a 30-cm long handle was fitted by upending the tube onto the cap and pressing firmly. The capsule container was nested on a vertically mobile platform formed from a modified beam balance. The platform was raised by depressing an extension of the beam. As this occurred, the needle of the Ovijector gun penetrated first the hole in the plastic cap and then the gelatin capsule. Following injection with 1ml ($5\mu\text{Ci}$) of solution the platform was lowered, the plastic cap removed, and the capsule transferred immediately into a solution of dry ice and acetone. Because the capsules were only approximately

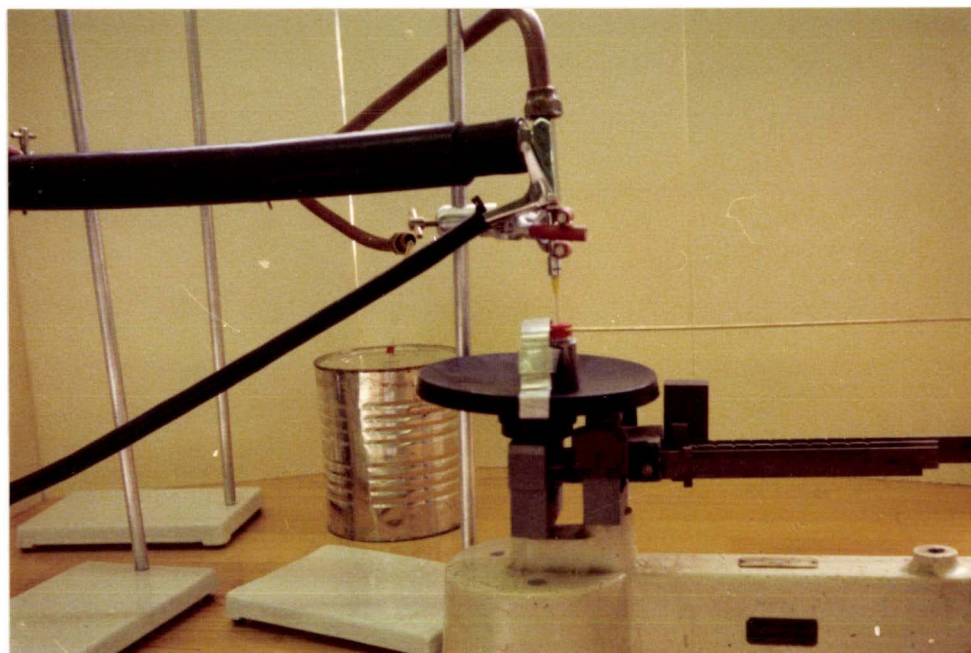


Plate 4.1 Equipment used for loading gelatin capsules with ^{32}P , showing capsule holder in position on the mobile platform of the modified beam balance.



Plate 4.2 Wooden template in position above the "hot line" with rods used to make isotope placement holes to required depth.

50% full they floated upright in the freezing mixture with minimal escape of isotope through the needle puncture. Once frozen, which took about 5-10 seconds, the capsules were placed in small insulated bins and stored in a freezer.

The above method was found to be rapid and safe, enabling ample shielding to be provided from the total of 21.25 m Ci used to fill the required 425 capsules.

It was intended that a small amount of KH_2PO_4 be added to the isotope solution (equivalent to $1\mu\text{g P ml}^{-1}$) to reduce the possibility of significant ^{32}P sorption on to glass- and metal-ware which would have diminished the potential activity of the available isotope. The ^{31}P was mistakenly added, however, at a rate equivalent to $1000\mu\text{gP ml}^{-1}$ of solution. The implications of this are discussed in Section 4.3.2.2.

4.2.3 Isotope placement

At each site a transect of five gelatin capsules were spaced at 5-cm intervals at the required treatment depth across slope. This spacing interval was selected as being suitable, based on the conclusions of Harries et al. (1974) who considered that P diffusion of up to a 2.5-cm distance in soil can occur after isotope addition. Holes to the required depth were made at right angles to the soil surface using a 4.5-cm thick wooden template and a 1.3-cm diameter metal rod (Plate 4.2). A thin metal rod marked the end of each transect which involved a total length of 30cm.

A frozen capsule was guided into each hole from a narrow nosed scoop and gently pushed to the bottom of each hole with a wooden rod. A small amount of pumice sand was added to ensure that no air pockets existed around the capsule and each hole was then back filled with soil from the relevant soil depth obtained at a nearby site.

4.2.4 Soil measurements

Just prior to isotope placement and at approximately 10 cm from the ends of each isotope transect, five cores of soil were collected from the relevant treatment depth. Three of these cores in each case were bulked for analysis of Olsen P (Section 3.2.6) and the remaining two cores were used for moisture content determination by oven drying overnight at 110°C.

4.2.5 Pasture harvesting

Pasture was harvested on two occasions; the first 2 days after isotope placement and the second 27 days later. At each time the pasture on the transect, or "hot" line, and in a band 3-cm wide on each side was trimmed over the length of the transect and collected as one sample. Similarly, pasture on 5-cm wide bands parallel to and at increasing distances from the transect were separately sampled. The exception was on sites adjacent to stock tracks where bands only in either an upslope or a downslope direction were harvested according to treatment. No measure of across-slope spread of P uptake was made.

Pasture was cut using battery-powered hand shears with the cutting edge reduced to 5-cm width and with a shield fitted to collect cut material. The operator was directly screened from the "hot" line as much as possible by a perspex shield (Plate 4.3). Sample weights were not recorded and analysis was done on a mixed pasture sample. This procedure was necessary because of both the difficulty of cutting and collecting all the pasture growing on each measurement band and secondly, because of the small sample size on some sites, especially 45° slopes. Within each stratum, however, pasture was considered suitably uniform for comparative measurements to be validly compared. Jackman and Mouat (1972) found that corrections for variable pasture growth on a flat-site did not affect relative root activity



Plate 4.3 Pasture on a 25° slope plot prior to harvest 29 days following isotope placement. Perspex sheet in position to shield operator from the "hot line" and battery-powered harvesting shears ready for use.

estimates. Direct, between strata comparisons, however, were not possible because of much larger differences in pasture composition and growth rates.

4.2.6 Measurement of ^{32}P activity

The recognized method of measuring ^{32}P activity in pasture samples involves acid extraction of total P, an aliquot of this being mixed with a scintillation cocktail for counting in a liquid scintillation counter (Dyer, 1974). It was considered that because of the large number of samples to be analyzed (approximately 600 per harvest) and the need for only comparative results a modified, more rapid method could be used. Consequently isotope activity was measured in pasture samples immersed directly in a scintillator, a technique not encountered elsewhere. Other forms of solid material, containing high energy β emitters (e.g., ^{32}P), have been measured in several ways (Dyer, 1974). For example, finely-divided solids derived from urine, plasma, and bone, have been dispersed in cocktail using cabosil, a fumed silica product. Various forms of precipitate have also been deposited on glass-fibre filter paper and mulched in a toluene scintillator for counting. In addition, biological samples containing high-energy β emitters are now routinely being analyzed using the more simple Cerenkov counting technique (White and Ellis, 1968; Cole, pers. comm.). The best results from the Cerenkov counting method, however, are obtained by wet-ashing the sample and by using an external standard to correct for colour quenching (White and Ellis, 1968). This was found to provide greater counting efficiency of ^{32}P in plant samples than by the preparation and counting of compressed dry briquettes (MacKenzie and Dean, 1950). All of the above methods were either unsuitable or considered to be too time consuming for use in the present study. An attempt was therefore made to develop a simple method of

obtaining repeatable, relative activity measurements from solid pasture samples.

An initial approach involved placing small, whole, undried subsamples of pasture in a scintillation cocktail and counting. This provided measureable activity that was generally related to the level of isotope present. Replication, however, was poor. Nevertheless, it did provide a measure of any activity present in pasture and therefore was used as a rapid indication of the extent (i.e., distance from the "hot" line) of ^{32}P uptake by pasture over the two-day period following isotope placement.

For the second harvest, however, a more-refined method was developed which gave reliable results relative to the acid-digestion technique. The results given in Section 4.3.1 involved the following method of pasture sample preparation and analysis.

Pasture was oven-dried overnight at 60°C and finely ground ($< 2\text{mm}$) within a forced-draught chamber. Approximately 0.1g of pasture, measured by volume for greater convenience, and 10ml of Triton-toluene scintillation cocktail (Patterson and Green, 1965) were placed in a counting tube and shaken well. This was allowed to stand for at least 1 hour before counting to avoid chemiluminescence contamination of isotope readings and to allow suspended solid pasture material to settle.

4.2.7 Processing of results

All results were expressed as cpm g^{-1} dry matter. Because of the extremely wide range of readings, results were transformed to logarithm values for statistical analysis. All results from within each stratum were assembled into a single analysis of variance and treatments (depth and distance from the hot line) ranked by the method of Duncan (1955). It was

noted, however, that where treatment replicates contained low or zero values, some situations occurred where the order of ranking true means was dissimilar to the ranking of logarithmic means. This anomalous situation can be encountered where an extremely wide range still exists in transformed logarithm values used for statistical analysis (Wright, pers. comm.). In order to remove this anomaly all values (x) below 100, and including zero values, were converted to logarithms (y) by the formula $y = \log(x + 10)$ to further condense the range for statistical analysis.

4.3 Results and Discussion

4.3.1 Sample preparation comparison

An increase in sample weight up to 0.05g increased the measured level of activity in finely-ground pasture but had no further effect, at least up to 0.2g (Fig. 4.1). The increase in level of measured activity associated with the increase in sample size up to 0.05g and the subsequent constant level of reading demonstrated the classic "self weakening" effect associated with an increase in size of β -active solid samples (I.A.E.A., 1964). The counting rate of samples increased at first with sample size because of increased total activity and then became constant as extra contributions from deeper layers were absorbed by side- and back-scattering effects. The level at which this occurs is termed the "infinite thickness" of the sample. For finely ground pasture used in this study it would appear to be approximately 0.05g. The level of ^{32}P activity (cpm) 24 hours following sample preparation was generally only fractionally less than that measured after only 1 hour and therefore could be considered stable at each sample size, at least over this period.

Subsample variability was low at all levels of activity and over all

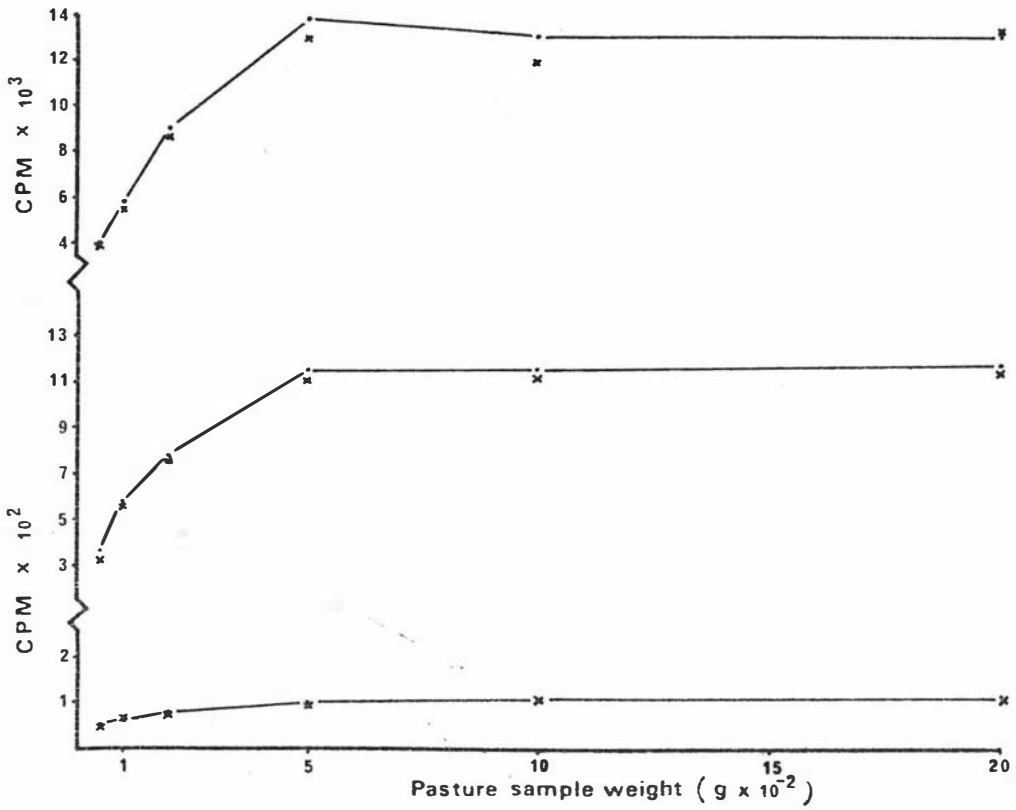


FIGURE 4.1 Effect of sample size on measured $^{32}\text{Pcpm}$ at three levels of activity; • = Reading 1 hour following preparation and x = Reading 1 day following preparation.

durations measured (e.g., the means of eight subsamples had coefficients of variation of the order of 5-7%).

The data obtained from 0.1-g ground pasture samples compared with digested samples showed that the counting efficiency of the former ranged from 7.9 to 9.7% over an approximately 50-fold range in ^{32}P content. For the purpose of the field trial the counting efficiency was regarded as constant at the selected sample size of 0.1g.

4.3.2 Field results

Before interpreting the results obtained in the field study it is necessary to consider the effect of the unintentionally high ^{31}P loading added to the ^{32}P isotope before placement.

At the first harvest two days after isotope placement, the high P level in the capsules would effectively have swamped the plant-available P supply from the surrounding soil at all depths. Uptake of P during this period could be considered to have predominantly occurred from the added P. Therefore, no correction for soil P status at each depth would have been required if this was the full duration of the trial.

For the final harvest, however, the assessed RRA (Table 4.2) was greatly affected by either inclusion or exclusion of a correction for "available" (Olsen) soil P at each depth (Table 4.3), as described by Jackman and Mouat (1972). The likely effect of the added carrier on available soil P must therefore be considered. The major objection to the application of ^{32}P with an associated ^{31}P carrier is that the added ^{31}P induces enhanced root proliferation (Newbould, 1969; Newbould and Taylor, 1964), and that this is relatively greater as plant-available soil P status decreases, i.e., with increased soil depth. As shown below however, the added ^{31}P in this study should not greatly affect the

conclusions drawn from RRA estimates based on measured soil P levels.

If the added P from each capsule could be assumed to spread into a sphere of about 5-cm diameter (Harries et al., 1974), then this would involve a soil volume of 65.5cm^3 which, for example, at the $1\frac{1}{2}$ -cm depth would be equivalent to 45.8g soil and at 22cm about 66g soil. The soil total P level in these spheres would therefore have increased by approximately 22 and $15\mu\text{g P g}^{-1}$ respectively. As demonstrated in Section 5.3. 3.1, the immediately plant-available portion (i.e., water-extractable P) of the added P would have decreased rapidly over 7 days, occurring at a faster rate where soil P status was lower, i.e., at greater depths. In the 27-day regrowth period following the first harvest, the greatest growth, and therefore P uptake, would have occurred in the latter half of this period due to the exponential pattern of pasture regrowth following close cutting (Brougham, 1956). It is likely then, that P uptake during the final harvest period would have been predominantly from "native" soil P, despite the relatively high level of added P. This is highly probable in the 0-3cm soil depth but relatively less so at greater depths. If the high soil P status to 3cm depth could be considered to have remained essentially unaltered, and to comprise the "actual" plant-available P source, then calculations show that any assumed increase in P status at greater depths would be reflected in a similar proportional increase in estimated RRA. For example, if the effective Olsen P status of the soil at 22cm depth of placement on 25° slopes was, due to added P, considered to be 10 instead of $3\mu\text{g P g}^{-1}$ (Table 4.3), then the recalculated RRA at that depth would increase to 1.1% compared with 0.5% (Table 4.2). This would similarly apply to any assumed changes in soil P level at other depths (excluding 0-3cm).

Corrected estimates of RRA based on measured soil P should therefore

present a more true picture than if it was assumed that added P was the predominant source of plant uptake. Any errors resulting from this assumption will lead to some overestimation of P uptake from subsoil and conversely, a slight under-estimation of relative root activity in top soil.

4.3.2.1 P uptake after 2 days

Pasture samples collected 2 days after isotope placement were used primarily to define the extent of pasture P uptake over that period. Although replicate variability was high, the results still provided a useful indication of the perimeter of the P uptake zone relative to depth. As expected, the level and spread of P uptake decreased with depth (Table 4.1).

^{32}P placed near the soil surface (i.e., 1½-cm depth) on campsites was taken up by pasture to a distance of 23cm away, and on 25° and 45° slopes to a similar distance downslope. The upslope zone on these latter strata was less well-defined but appeared limited to about 18cm on 25° slopes and 13cm on 45° slopes, although in both instances some activity was measured to a distance of 23cm upslope from the isotope transect.

On all strata there was a lower, but still appreciable uptake of P placed at 22cm depth, but only by pasture growing within about 13cm of the transect. Pasture adjacent to stock tracks showed a similar spread of uptake both from the 1½-cm soil depth (23cm downslope and 18cm upslope) and the 11-cm depth (18cm downslope and upslope) as that by pasture on mid 45° slopes.

4.3.2.2 P uptake after 29 days

Within any one stratum, the data from all treatments (i.e., each depth of placement and distance away of pasture P uptake) were

Table 4.1 Mean ^{32}P levels (cpm) measured in whole, undried pasture two days following isotope placement in soil at various depths.

Stratum	Placement depth (cm)	Distance from "hot line" (cm)									
		Upslope					Downslope				
		23	18	13	8	3	3	8	13	18	23
Campsite	1½	30	240	630	2920	4900	3220	180	260	10	
	5	10	80	340	1170	2710	680	70	90	20	
	11		10	50	60	460	170	40	10		
	22		50	80	100	300	50	40			
25° slope	1½	10	20	190	350	15980	2120	820	130	60	
	5		10	50	330	2580	230	100	80	10	
	11	10	10	60	190	560	400	270	50	40	
	22			40	180	500	100	50			
45° slope	1½	20	20	160	1060	9970	2140	330	60	60	
	5	10	20	70	240	1420	310	110	20	10	
	11		40	60	60	1500	100	40	40		
	22		20	120	80	360	110	40	10		
45° slope above track	1½		30	70	300	8720					
	5		20	60	220	1210					
	11			40	70	410					
45° slope below track	1½					8650	3420	240	370	50	
	5					1160	1240	130	40		
	11					990	1070	250	80	20	

Table 4.2

Relative root activity (%) at various soil depths on each stratum estimated both with and without correction for soil Olsen P values

Soil depth (cm)	Campsites		25° slopes		45° slopes	
	Uncorrected	Corrected	Uncorrected	Corrected	Uncorrected	Corrected
1½	57.9	66.0	53.8	88.1	44.4	82.4
5	28.0	29.1	25.8	9.7	27.9	14.6
11	11.3	4.0	13.5	1.7	17.3	2.3
22	2.8	0.9	6.9	0.5	10.4	0.7
	Slope above track		Slope below track			
	Uncorrected	Corrected	Uncorrected	Corrected		
1½	51.4	86.4	47.1	78.7		
5	29.5	11.5	30.1	4.0		
11	19.1	2.1	22.9	4.0		

Table 4.3 Soil characteristics on each stratum at trial commencement (13.9.76) and also soil moisture content at final harvest - North aspect

Stratum	Sample depth (cm)	Olsen P ($\mu\text{g g}^{-1}$)	pH	Soil moisture content	
				at 13.9.76 (% by wt)	at 12.10.76 (% by wt)
Campsite	0-3	169	6.2	106.7	142.6
	3-7	154	5.2	65.8	71.5
	7-15	53	4.9	42.0	46.8
	15-30	44	4.6	34.8	44.3
25° slopes	0-3	98	6.2	100.6	105.9
	3-7	22	5.5	44.0	60.9
	7-15	8	5.2	38.8	46.1
	15-30	3	5.0	39.3	42.6
45° slopes	0-3	110	6.3	67.5	76.1
	3-7	31	5.3	46.6	52.0
	7-15	8	5.1	43.4	43.5
	15-30	4	5.2	34.5	40.0
Stock Track (inside edge below 45° slope)	0-3	125	6.2	99.8	83.8
	3-7	29	5.7	57.1	55.7
	7-15	8	5.4	40.0	38.7
Stock Track (outside edge above 45° slope)	0-3	105	6.3	94.9	101.5
	3-7	36	5.4	52.7	69.0
	7-15	11	5.2	40.7	45.0

assembled into a two-dimensional measure of RRA by pasture. Root activity at $1\frac{1}{2}$ -cm depth predominated in all strata, representing 66.0, 88.1, and 82.4% of total uptake on the campsite (Fig. 4.2A), 25° slopes (Fig. 4.2B), and 45° slopes (Fig. 4.2C), respectively. Relative P uptake decreased sharply and significantly ($P \leq 0.05$) with each depth increment. This decline was more marked on the slopes than on the campsites and appeared to reflect the more gradual decline in soil P levels on the latter stratum, i.e., RRA was concentrated in soil zones of highest P status.

Pasture within 13cm of the placement sites accounted for 90.8, 95.5, and 90%, of the total RRA on the campsites, 25° slopes, and 45° slopes, respectively, suggesting that the spread of root activity was similar on all strata. Whereas the overall P uptake patterns were similar on all strata, the lateral distribution of this activity was affected by slope. Campsites were on flat to undulating land but all plots had some slope and therefore P uptake could be related to an upslope or downslope end of the plot. (Fig. 4.2A). This slight slope appeared to have some effect in that P uptake was measured in pasture to a greater distance upslope at all depths. This resulted in significantly ($P \leq 0.05$) greater uptake only at the 5-cm depth.

On 25° slopes (Fig. 4.2B), the RRA at $1\frac{1}{2}$ -cm depth downslope was not significantly different to that on the upslope side. At all greater depths, however, both the spread and level of activity were significantly greater in pasture uptake from 5-cm ($P \leq 0.05$), 11-cm ($P \leq 0.05$), and 22-cm depths ($P \leq 0.01$) on the upslope side of the "hot" line. ^{32}P activity in pasture was measured to greater distances than shown in Fig. 4.2B (i.e., upslope to 18-23cm distance at 11-cm depth and 23-28cm distance at 22-cm depth; downslope to 3-8cm distance at 22-cm depth, 8-13cm distance at 11-cm, and 13-18cm distance at 5 and 11-cm depths), but in each case these represented less than 0.1% RRA.

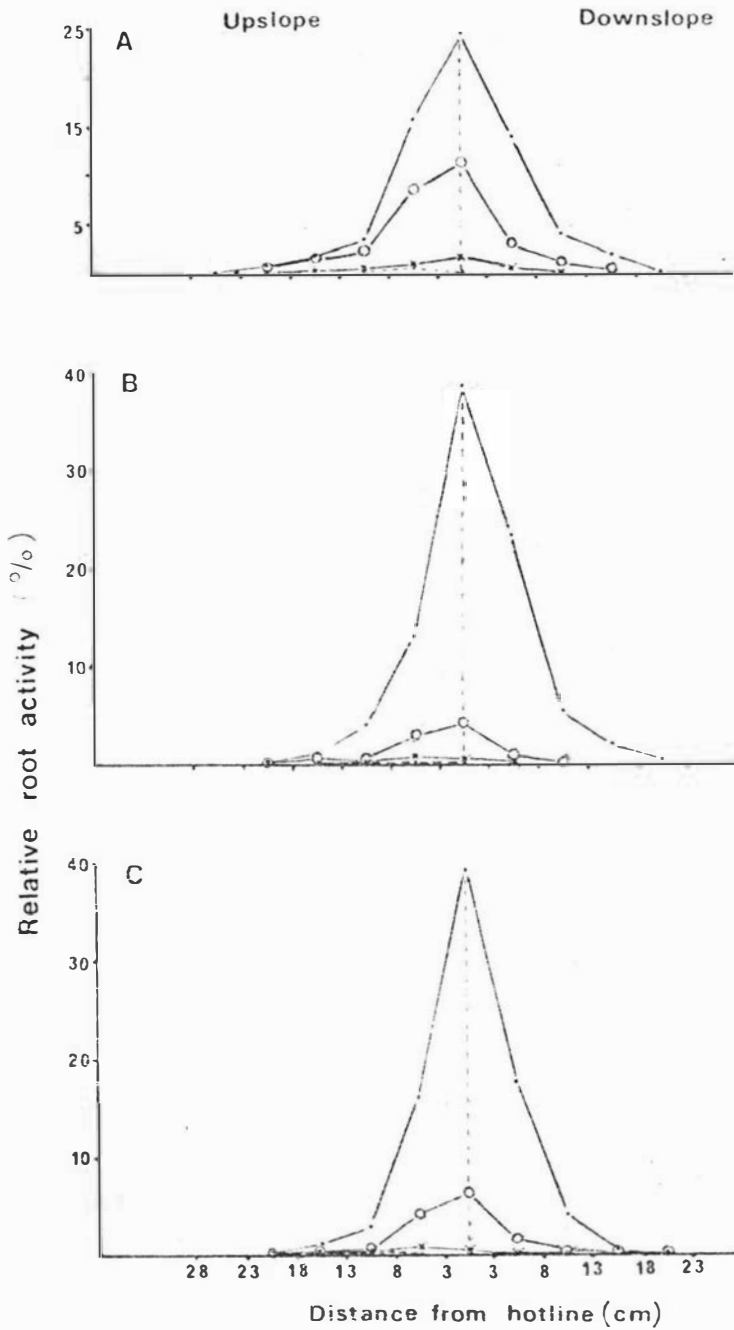


FIGURE 4.2 Lateral and vertical distribution of relative root activity (%), (corrected for soil P status at each depth); A = North campsites, B = North 25° slopes, and C = North 45° slopes; · — · 1.5cm depth, o — o 5cm depth x — x 11cm depth, and · --- · 22cm depth.

On 45° slopes (Fig. 4.2C) both upslope and downslope RRA was similar at $1\frac{1}{2}$ -cm depths ($P \leq 0.10$). At the 22cm depth of placement, the RRA in pasture upslope was higher and measured further away from the transect (23-28cm) than that in pasture downslope (to 3-8cm). Because of extreme variability between replicates at this depth the difference was not significant. This indicated that the penetration of active pasture roots to 22-cm depth comprised only a relatively sparse network and that uptake of P was also extremely variable, although at a very low RRA level. Increased variability in ^{32}P uptake from greater depth as also recorded by Burton (1957) may be associated with the marked drying and cracking of the subsoil that can occur during later summer and autumn. Uptake variability at depth, however, may also be associated with some suppression and subsequent recovery of root elongation following defoliation of shoot material, as demonstrated by Evans (1972) with ryegrass. The greater variability in P uptake from lower soil depths suggests that greater replication is needed in such situations to achieve the same accuracy of measurement as was obtained in the topsoil.

Relative root activity in pasture adjacent to stock tracks was measured to only 11-cm depth (Fig. 4.3). Unless the data in Fig. 4.2 are similarly recalculated to only this depth, they cannot be directly compared. Because of the very low proportion of root uptake from the 22cm depth, a direct comparison would, in this instance, introduce little error.

The RRA at $1\frac{1}{2}$ -cm depth was similar, both upslope and downslope of track sites. As the tracks were relatively level across their width, P placed at greater depths was correspondingly much further away from plants slope of the track than when placed on a 45° slope at similar depths

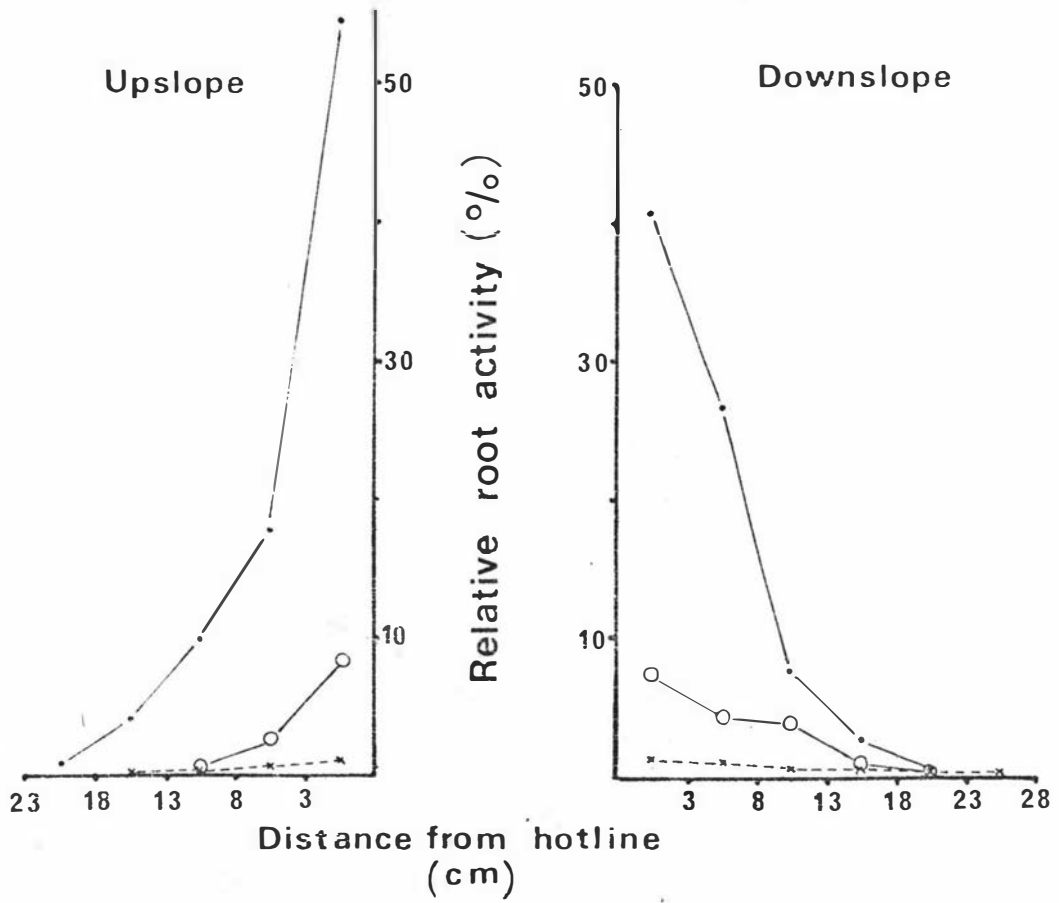


FIGURE 4.3 Lateral and vertical distribution of relative root activity (%) adjacent to stock tracks (corrected for soil P status at each depth);
 · — · 1.5cm depth, o — o 5cm depth, x --- x 11cm depth.

normal to the slope. Consequently, ^{32}P placed at both 5 and 11-cm depths on the track was available to a shorter distance upslope, and at 11-cm depth only, to a greater distance downslope, on the adjacent 45° slope than shown in Fig. 4.2. In addition, the results demonstrate that P placed at 11-cm depth on the outside edge of tracks was available to plants further downslope (23-28 cm) than when placed at more shallow depths.

4.3.2.2.1 Zones of relative root activity. Because the isotope placement depths of $1\frac{1}{2}$, 5, 11, and 22 cm represent the mid points of soil zones 0-3, 3-7, 7-15, and 15-30cm, respectively, root activity levels at each of these depths should be related to each soil zone on each stratum as shown in Fig. 4.4.

A more correct picture of RRA in each soil sampling zone will therefore be obtained by integrating the relevant area under each part of the various curves, assuming that P uptake at the midpoint is representative of the zone. Such integration is necessary to overcome bias introduced by the variable distances between isotope placement depths. Where distances are equal between placement depths, the RRA may be related directly to the encompassing soil zone.

Integrated results show that the RRA level ranged from 52.3, 69.9, and 66.5% in the 0-3cm soil depth to 4.3, 3.4, and 4.0% in the 15-30cm depth in the campsites, 25° slopes, and 45° slopes, respectively. The effect of such integration can be seen by comparing these values with the relevant results in Table 4.2 for RRA at each depth.

The results in Table 4.2 are similar to those reported for browntop and white clover root distribution by Jackman and Mouat, (1972). These workers related root activity at a particular depth (e.g., approximately 80% at 2.5cm depth) to the soil above, rather than to a soil zone

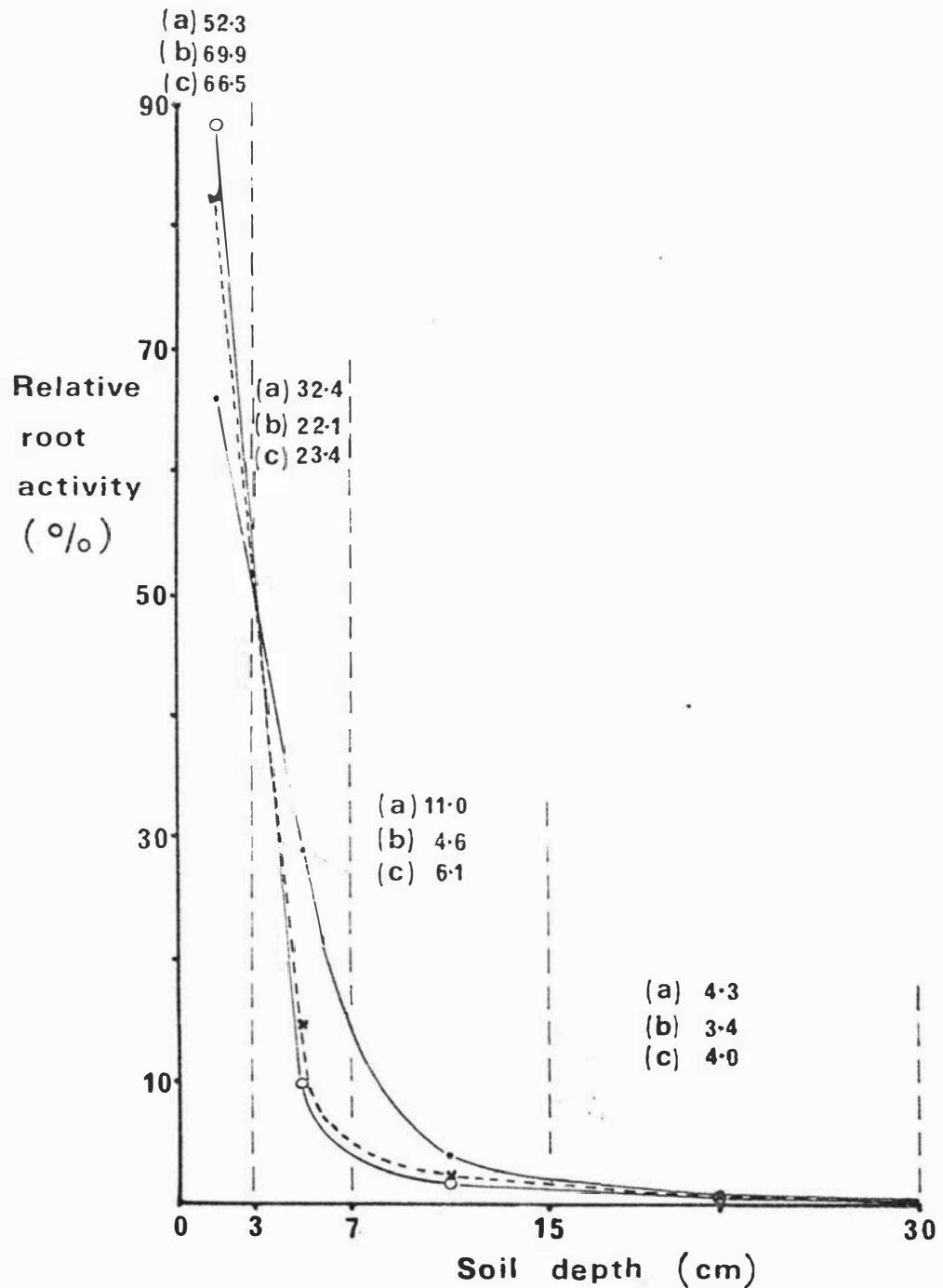


FIGURE 4.4 Relative root activity at each soil depth for the north campsite (\cdot — \cdot), north 25° slopes (\circ — \circ), and north 45° slopes (\times --- \times), and estimated integrated relative root activity for each soil depth range on (a) north campsite, (b) north 25° slope and (c) north 45° slope.

encompassing this point. Such integration would have reduced their RRA estimates by a similar order to that shown in Fig. 4.4.

4.3.2.2.2 Direction of predominant root activity. The two-dimensional measure of RRA at the four depths and at various distances away from the isotope placement sites was derived from measurements of pasture plants growing on or adjacent to the "hot line" which had roots exploring these placement sites. If the pasture within each stratum is considered to be relatively uniform in growth and botanical composition, this same measure can represent the spread and depth of RRA of a single plant growing on the "hot line" transect. Where the root uptake pattern is not symmetrical, however, as was the situation on all three strata, the pattern must be inverted so that the upslope root uptake activity of a single plant is represented by that actually measured in pasture downslope of isotope placement.

Furthermore, the effect of slope on RRA distribution is more clearly demonstrated if the mid point of spread of such activity is plotted in relation to the ^{32}P placement sites at each depth.

The data in Fig. 4.5 indicate that the direction of predominant root activity was not normal to the soil surface but tended to be nearer to the vertical on all strata. Although root growth was predominantly geotropic on all strata, the difference between the vertical (90°) and the angle of predominant root activity tended to increase with steepness of slope, i.e., 6° on the 25° slope and 15° on the 45° slope.

There are two possible explanations for this pattern of root growth. First, as previously discussed, the soil tends to dry and crack in drought periods. Because it is likely that soil drying will occur normal to the

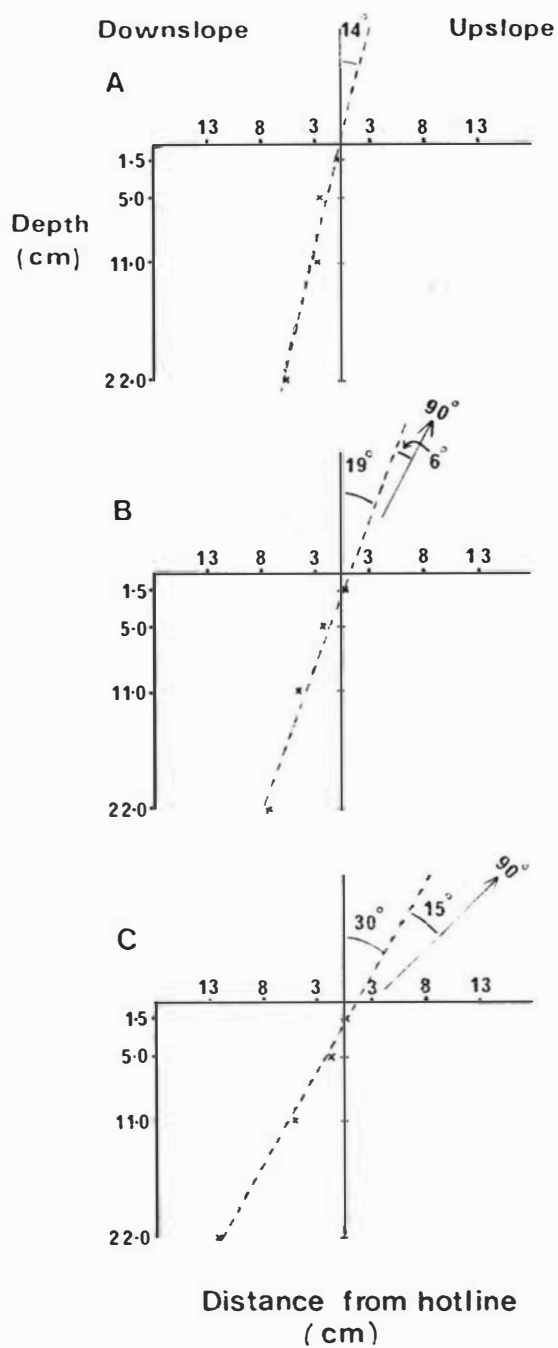


FIGURE 4.5 Calculated mid point of lateral root activity distribution at each sampling depth and derivation of the direction of predominant root activity on each stratum. A = Campsites, B = 25° slopes, C = 45° slopes.

soil surface, such cracks will tend to follow this direction. Therefore, both the direction of drying and the formation of such cracks would encourage subsoil root development in particular, to be more normal to the surface than would otherwise occur and especially after soil rewetting which would also tend to follow soil cracks. The second, but less likely possibility is that there may be appreciable downslope movement of the topsoil relative to the subsoil layers which would tend to make inherently vertical root penetration patterns more normal to the slope. Although no evidence has been produced to support either of these explanations it is probable that the first may have the greater credence as no obvious signs of surface soil movement are present.

The direction of predominant root activity has implications for soil sampling on hill slopes. If associated with assessment of plant P availability, sampling should validly represent such uptake zones. Soil samples taken normal to the slope will obviously not do this, the error increasing with the depth of sampling and being greater on steeper slopes. Such sampling will tend to indicate more shallow horizons than the pasture actually explores.

If samples are taken normal to the soil surface, and this is often easiest on very steep slopes, then a correction factor (e.g., 1.06 on 25° slopes; 1.15 on 45° slopes) should be applied to validly represent the sampling depth. This would only be necessary on 25° slopes for samples deeper than 7cm and 45° slopes for samples deeper than 3cm. At more shallow depths the correction would be less than the probable error in sample length (i.e., about 0.5cm). Samples taken vertically would involve much smaller errors in all situations and generally obviate the need for correction factors. While such corrections as suggested should improve sampling precision it is likely that the difference would be marginal

relative to the field variability of hill soils, as indicated from analysis of samples from the study area (Section 3.3.5).

4.4 General Discussion

It is apparent from the results on each stratum that the full effective root distribution pattern was measured in the study and it is unlikely that soil P at any depth greater than 30cm participated significantly in the P cycle. The surface concentration of root activity can be associated with the zone of predominant P mineralization and also to a large extent, with the effects of nutrient return to slopes. Fertilizer P has a low mobility in the soil and therefore remains predominantly near the surface. In addition, urine returned to slopes potentially covers a larger area than on flat land and consequently the associated supply of N and K, being at lower effective application rates, would penetrate to a more shallow depth than on flat sites or camp areas. Under such conditions it could be expected that pasture roots would become highly concentrated in the soil surface zone.

In this study it was shown that 84.7, 92.0, and 89.9% of TP uptake by mixed pasture on campsites, 25° slopes, and 45° slopes, respectively, was from the surface 7 cm of soil. The high proportion of total P taken up from a shallow soil depth agrees with the results obtained by Jackman and Mouat (1959) with browntop and white clover and Harries et al. (1974) with ryegrass. In contrast, Halm et al. (1972) found in rangeland pasture that a soil depth of 30cm was required to encompass 90% of P uptake activity and that some uptake was measured from as deep as 60 to 120-cm soil depth.

Halm et al. (1972) also stressed the importance of available soil moisture to the uptake of P by plants. The very high proportion of TP,

and probably other nutrient uptake by vigorously growing pasture that was obtained from the surface 7cm of soil reflects the vulnerable dependence of pasture on all strata on adequate levels of soil moisture. This is particularly the case on slopes where the greater bulk of P uptake occurs from the 0-3cm soil depth. In this study uptake of P from all depths was not limited by inadequate soil moisture because ample rainfall over the trial period (118.5 mm measured at the Whatawhata meteorological site 500m distant) maintained the soil at or near field capacity (Table 4.3). The topsoil (0-7cm) on the north aspect, however, may dry out to below wilting point in summer and early autumn (Gillingham, 1973). At these times it would be expected that a larger proportion of the P requirements would be derived from greater depths, as was recorded by Uyo (1974) who calculated the RRA in 0-5cm depth soil to be about 96% in spring but only 65% in autumn.

The extremely high P inputs to campsites from predominantly dung and fertilizer appear to have encouraged a less surface-orientated root system than on slopes. This is also associated with a slightly greater depth of topsoil on some campsites. The possibility of achieving generally deeper root penetration on slopes by topdressing, where net P transfer losses also have to be compensated for, would be prohibitive in terms of the amount of fertilizer required.

An alternative approach towards reducing pasture vulnerability to drought is to adopt management practices or encourage pasture species that will maximise root depth and or conserve available moisture. More lenient grazing in summer and autumn, although difficult to practice in times of pasture shortage, will maintain associated deeper root penetration (Evans, 1971) and improve plant persistence by more prolonged access to

moisture at lower soil depths. The encouragement of white clover at the expense of browntop should also tend to reduce the rate of soil moisture loss and therefore increase the associated relative availability of P (Jackman and Mouat, 1972).

A further possibility is to stimulate the activity of subsurface-casting earthworm species (e.g., Allobophora caliginosa, J.A. Springett, pers. comm.) perhaps by use of lime. Such casting activity would result in mixing of surface and deeper soil layers and thereby promote improved conditions for deep plant root penetration.

The lateral spread of roots in an upslope or downslope direction from the crown was not as great as distances recorded on flat sites (up to 30cm; Troughton, 1957). The greater part of P uptake in the present study, however, was from distances of less than 15cm from P placement. The lateral extent of uptake of P by pasture plants therefore appears similar to that for N and S uptake. Vallis et al. (1973) found that pasture plants recovered little ^{15}N at distances greater than 15 to 30cm from the placement area. Similarly, Goh et al. (1977) concluded that most uptake of ^{35}S was from within 15cm of the site of application. If the effective root spread in any direction could be considered to be about 13cm from the crown (encompassing about 90% of total root activity), then the effective uptake area for any one plant could be approximately 530cm^2 . It would be expected that any fertilizer, litter, dung, or urine falling on any one spot could be potentially available to all surrounding pasture encompassing such an area. This has implications to the dung return intervals estimated in Section 3.3.2.2. In those calculations, dung was considered to cover, and contribute P to, an area of 100cm^2 per defaecation. As a result of the above estimates the effective dung return area must be

considered as nearer 500cm^2 and therefore the dung return intervals shown in Table 3.8 should be divided by five to present a more realistic estimate.

The spread of roots from plants growing downslope into soil under tracks could provide an additional source of P to a narrow strip to pasture in such situations. This would be especially so when soil on tracks was of a higher P status; a situation likely to apply after a long period of topdressing and dung return associated with continued pastoral use. Again, such an advantage would be most pronounced during periods of drought.

SECTION 5

THE ASSESSMENT OF SOME P SORPTION AND DESORPTION
CHARACTERISTICS OF SOILS FROM THE FIELD TRIAL AREA

5.1 Introduction

The above-ground components of the P cycle in grazed hill-country have been shown to be affected to a large degree by topographic situation (Section 3). Plant uptake of P and relative root activity (RRA) have also been measured (Section 4), both with respect to soil depth and distance from the plant crown. Similarly, both seasonal and annual estimates have been made of the amounts of P returned in litter and dung to differing hill strata. Field measurements were made over a period of approximately one year. The relevance of these results will depend to a large extent on the ability of the soil on each stratum to maintain a similar level of plant-available P in subsequent years. This will depend on the continued replenishment of the soil solution by net desorption processes but also on the effectiveness of fertilizer P, and P returned in dung and litter in correcting any soil deficiency. The amount of applied P and the P desorption characteristics of the soil would influence this situation. Using soils from the field trial area a programme was therefore planned first to assess some of the factors affecting P desorption into the soil solution, as measured by water-extractable P; second the relationship between water-extractable P and other forms of "native" soil P, as reflected in the rate and extent of P exchange between these forms; and third to assess the fate of applied P as reflected by changes in water-extractable and Olsen P levels.

It has been shown that the change in final soil solution P concentration resulting from either P addition or removal is proportional to the solid phase P status (Section 2.1.2). The soils of the field trial area have a

history of regular and more than adequate topdressing with superphosphate, particularly in recent years. The high levels of different forms of soil P (Section 3.3.5), and of water-extractable P in particular, suggest that P sorption sites in region I of these soils, as defined by Ryden and Syers (1975a), have been filled and that predominant sorption of added P, or desorption of soil P, would occur in regions II and III. This would particularly be the case for campsite topsoils. From sorption isotherm studies using the Langmuir equation and from subsequent desorption measurements, Ryden and Syers (1975a) concluded that P equivalent to that in region III can be removed from soil by two successive 1-hr water extractions (40:1 water:soil ratio). If this was the case, further continued sequential extraction of P would be expected to be dominated by region II desorption characteristics.

The extent to which P sorption exhibits predominantly single region characteristics will depend on the extent to which region II sorption sites are saturated and therefore the proportion of added P that is sorbed in region III. If a large proportion of added P rapidly becomes non-extractable by two successive 1-hr extractions (at a 40:1 water:soil ratio) then assuming region I sorption sites are filled, as previously discussed, it would be expected that a very high proportion of the added P will be sorbed in region II. In this situation, P sorption would be dominated by single region characteristics. Such being the case, the predominant P desorption and sorption characteristics of a soil of moderate to high P status should be qualitatively simulated by a simple single 'region' model. In order to test this hypothesis a single 'region' Langmuir model was constructed (Appendix VI) and used to simulate some of the P desorption and sorption experiments conducted in the laboratory and the results of both were compared.

The laboratory experimental programme had the following objectives:

- (1) Measurement of P desorption - to assess some conditions affecting the removal of labile soil P, as defined by that extractable in water.
- (2) Assessment of exchange reactions - to examine some factors affecting the rate and extent of P exchange, and therefore also equilibrium conditions within a soil.
- (3) Measurement of P sorption - by addition of P from various sources and examination of the water-extractable and Olsen P levels as they reflect not only the net effect of applied P, but also the component contributions of applied P and previously sorbed P to these net effects.

The soils examined were from contrasting strata in order to evaluate the effect of P status on the above measurements. Because soils from slopes occupy the greatest proportion of each hill paddock, most measurements were made in these soils.

5.2 Materials and Methods

5.2.1 Laboratory experiments

Soil samples for these experiments were collected to a depth of 7cm from each stratum of the field trial area (Section 3). This depth range represented the zone of major root activity (Section 4) and therefore was of greatest agronomic interest. Soil was air dried to approximately 5% moisture content by weight and sieved to pass a 2-mm sieve.

5.2.1.1 Measurements of P desorption

5.2.1.1.1 Effect of water:soil ratio and extraction

period on desorption of P. Soil from the North aspect 25⁰ slope was used to assess the effect of water:soil ratio and

duration of shaking (end-over-end at 45 r.p.m.) on the amount of DIP. The water:soil ratios used were 20:1, 40:1, 60:1, and 80:1, on an oven-dry soil basis and shaking involved either $\frac{1}{2}$, 1, or 2 hour periods. The 2-hour extraction was repeated at all ratios. The DIP concentration of each extract was measured following centrifugation and filtration (Section 3).

5.2.1.1.2 Effect of successive extractions with water on desorption of P. Six successive half-hour extractions of DIP from a North aspect 25° slope soil were made using water:soil ratios of 20:1 and 40:1. In a similar experiment using a 45° slope soil, 13 successive half-hour and 8 successive 1-hour extractions of DIP at a water:soil ratio of 40:1 were made.

5.2.1.1.3 Effect of antecedent soil moisture content on the desorption of P. During previous experiments it became apparent that the amount of DIP was affected by antecedent soil moisture conditions. This effect was examined in more detail by wetting air-dried soil from all strata to 90% field capacity and incubating for 2 days. The soil was sampled in an air-dry condition and subsequently after incubation for 1 and 2 days at 90% field capacity. The North aspect campsite and 45° slope soils were also sampled after incubation for 12 days. These two soils were then redried to an air-dry condition and sampled 2 days later.

Water-extractable P was removed by shaking at a 40:1 water:soil ratio. An extraction period of $\frac{1}{2}$ hour was used following the results of experiments in Section 5.2.1.1.2 which showed that DIP was little affected by shaking periods ranging from $\frac{1}{2}$ to 2 hours.

5.2.1.2 Evaluation of P exchange reactions

5.2.1.2.1 Fate of applied carrier-free ^{32}P . Carrier-free ^{32}P

was applied to air-dried soil from the North aspect 25° slope in sufficient water to reach 90% field capacity (measured as moisture content at 50-mm tension) and thoroughly mixed. After $1\frac{1}{2}$, $6\frac{1}{2}$, and 24 hours, DIP (40:1 water:soil ratio on an oven-dry basis shaken for 2 hours), bicarbonate-extractable P (modified Olsen), total inorganic P (40:1 $1\text{NH}_2\text{SO}_4$:soil ratio on an oven-dry basis shaken for 2 hours), total P after ignition (550°C for 2 hours and extraction with 40:1 $1\text{NH}_2\text{SO}_4$:soil ratio as for inorganic P determination), and also total P as determined by Na_2CO_3 fusion (Syers et al., 1968) were measured.

Suspensions from each extraction were centrifuged, filtered, and sub-sampled for measurement of ^{31}P content, as described in Section 3. For the determination of ^{32}P activity a 1-ml aliquot was added to 10ml of triton-toluene scintillation cocktail (Patterson and Green, 1965) in a counting vial. Isotope activity was determined using a Beckman LS-350 liquid scintillation counter (discriminator channel opening at range 30-1000 and Gain setting on 490). Counting efficiency varied with extract type and was determined by addition of known isotope standards to non-labelled samples of the appropriate extracts. As a safeguard, an external standard was also used with an automatic quench to ensure that all samples of each extract type exhibited similar counting efficiencies.

5.2.1.2.2 Effect of soil P status on net sorption of applied carrier-free ^{32}P from soil solution. Carrier-

free ^{32}P was added to air-dried soil from South aspect campsites, North aspect campsites, and 45° slopes in sufficient water to reach 90% field capacity, and thoroughly mixed. These soils represented a wide range in

soil P status. At intervals up to 96 hrs of incubation (at approximately 20°C), all soils were analyzed for DIP (40:1 water:soil ratio) and bicarbonate-extractable P (modified Olsen). The North aspect campsite and 45° slope soils were similarly sampled after incubation for 12 days. Each extract was also analyzed for total ^{32}P isotope content.

5.2.1.3 Measurements of P sorption

5.2.1.3.1 Effects of the addition to soil of water-soluble P from various sources. Water-soluble $\text{P}^*(^{31}\text{P})$, from superphosphate, dried sheep faeces, and dried ryegrass, (litter), was "labelled" with carrier-free ^{32}P and added to soil previously incubated at field capacity for 11 days. These three treatments were compared with the addition of carrier-free ^{32}P only (control treatment) to similarly incubated soil. Each treatment was replicated 5 times (100-g sample per replicate).

The soils used were 0-7-cm depth samples from North aspect campsite and 45° slopes. The "plus P" treatments received a total of $88.5\mu\text{g } ^{31}\text{P g}^{-1}$ with an inorganic P content (expressed as a % of total P as follows):

superphosphate	100%	inorganic P
dung	89%	" "
litter	89%	" "

^{32}P was added in each treatment at a rate equivalent to $0.6\mu\text{Ci g}^{-1}$ soil. Following thorough mixing, soil was allowed to dry to approximately 60% field capacity (% by weight). Sampling (duplicates of 2-g oven dry equivalent per treatment) was conducted 1, 3, 7, 14, and 42 days following ^{32}P application. Samples were analyzed for total water-extractable ^{31}P (at both 10:1 and 40:1 water:soil ratios shaken for $\frac{1}{2}$ hour) and bicarbonate-extractable inorganic ^{31}P (a 20:1 NaHCO_3 :soil ratio shaken for $\frac{1}{2}$ hour).

* single extract.

5.2.2 The Langmuir Model

The original Langmuir model for describing the adsorption of gases on solids was based on the following assumptions (Moore, 1966):

- (1) "The solid surface contains a fixed number of adsorption sites. At equilibrium at any temperature and gas pressure, a fraction of the sites is occupied by adsorbed molecules, and a fraction $(1-\theta)$ is not occupied,
- (2) Each site can hold one adsorbed molecule,
- (3) The heat of adsorption is the same for all sites and does not depend on the fraction covered, and
- (4) There is no interaction between molecules on different sites. The chance that a molecule condenses at an unoccupied site or leaves an occupied site does not depend on whether or not neighbouring sites are occupied".

In applying these assumptions to the sorption of P from solution by a soil, they can be restated as follows:

P sorption rate (SR) from solution \propto solution P concentration
 \times proportion of sites on the solid surface that are unoccupied.

$$\text{i.e., } SR \propto (P_{\text{conc}}) (1 - \theta)$$

Similarly, the desorption rate (DR) of P from the solid to solution is proportional to the proportion of filled sorption sites.

$$\text{i.e., } DR \propto \theta$$

These can be expressed in the following form:

$$SR = K_1 (P \text{ conc}) (1 - \theta) \text{ --- (5.1)}$$

$$\text{and } DR = K_2 (\theta) \text{ --- (5.2)}$$

This model was programmed on a Burroughs B6700 computer using C.S.M.P (shown in detail in Appendix VI).

Arbitrary values were used for the appropriate constants and soil parameters, and the model was operated until an equilibrium was reached, i.e., until $SR = DR$.

"Experiments" conducted with the model were as follows:

5.2.2.1 Measurements of P desorption (Langmuir model)

The total amount of P removed by two-extractions at a ratio of 40:1 was compared with that removed by a single extraction at 80:1.

This was accomplished by considering the system at equilibrium, lowering solution P concentration to zero, and allowing the model to restore equilibrium. For a repeat extraction the level of P on the solid was reduced to the new equilibrium level and P concentration again lowered to zero. For an 80:1 extraction the solution:solid ratio was adjusted appropriately.

5.2.2.1.2 The effect of repeated extractions on removal of water-extractable P (Langmuir model). A

series of 5 successive extractions at a 40:1 ratio was conducted in order to establish the shape of a P-exhaustion curve and to assess any effect of P status on this relationship.

5.2.2.2 Fate of an applied 'label' (Langmuir model).

The exchange occurring within a dynamic system at equilibrium is most easily assessed in terms of the time required for a small amount of 'labelled' P added to the soil solution to be similarly at equilibrium within the system. In practice, isotopes provide the 'label'. In the model a small amount ($0.001\mu\text{g ml}^{-1}$) of labelled P was added to the solution. "High" and "Low" P status systems were compared in terms of the time taken for the added 'label' to reach equilibrium and on the level of label remaining in solution at this time.

5.2.2.3 Measurements of P sorption (Langmuir model)

5.2.2.3.1 The fate of added P. The effect of adding two rates of P (80 $\mu\text{g P}$ and 120 $\mu\text{g P}$) to both High and Low P status systems was studied. The effect was measured both in terms of the final concentration of P in 40ml of solution and the total P on the solid at equilibrium.

5.3 Results and Discussion

5.3.1 Measurements of P desorption

5.3.1.1 Effect of water:soil ratio and extraction period on desorption of P

Water-extractable P increased with an increase in water:soil ratio from 20 to 80 (Fig. 5.1). Doubling the extraction ratio had a smaller effect than a second extraction at the same ratio in removing additional P. This effect was more pronounced at high ratios. For example, with a 2-hour shaking, the P extracted by a single 40:1 extraction (6.9 $\mu\text{g P g}^{-1}$) was only marginally less than the total removed by two 20:1 extractions (7.3 $\mu\text{g P g}^{-1}$). The difference was greater, however, when comparing the P removed by an 80:1 extraction (10.1 $\mu\text{g P g}^{-1}$) with that removed in a repeated 40:1 extraction (12.5 $\mu\text{g P g}^{-1}$). The difference between the amounts of P removed by the two lower extraction ratios was not significant i.e., only 0.4 $\mu\text{g P g}^{-1}$. This compared with a difference of 2.4 $\mu\text{g P g}^{-1}$ at the higher ratios, i.e., a 6-fold increase for a 2-fold increase in ratio.

The greater amount of P released in 2 successive extractions, compared with that removed by a single extraction of the same total volume, is in agreement with the results from the Langmuir model (Table 5.1) and demonstrates that the effect was due only to the greater desorption

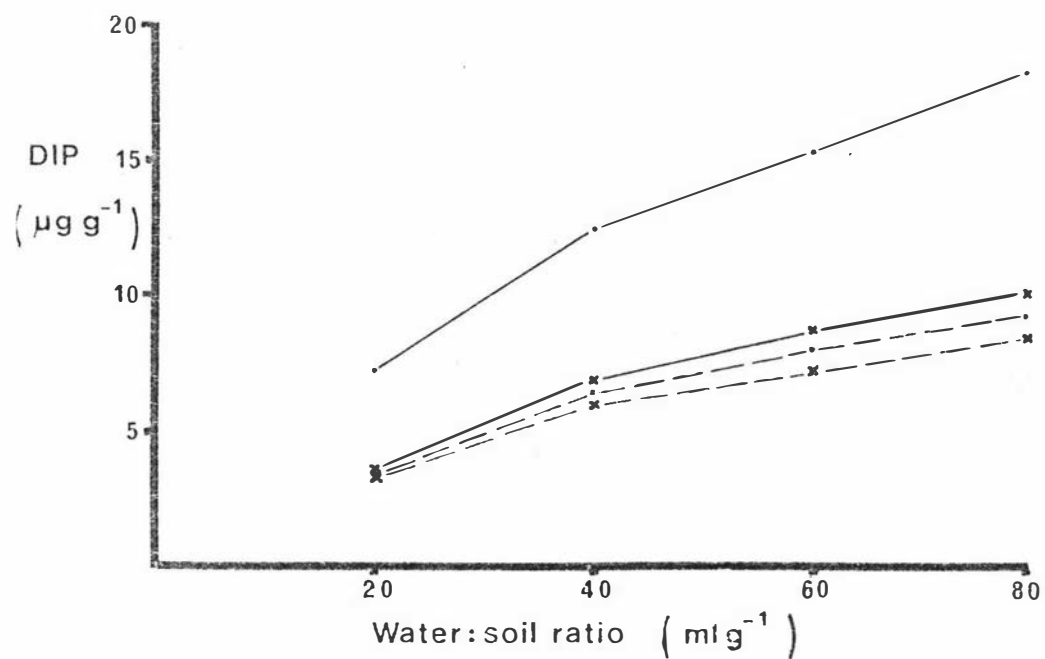


FIGURE 5.1 Effect of water:soil ratio and extraction period on desorption of P from north 25° slope soil; x -- x 2-hr extraction, · — · total from two 2-hr extractions, · --- · 1-hr extraction and x -- x 1/2-hr extraction.

Table 5.1 Effect of solution:soil ratio on extraction of P (Langmuir model)

Soil	2 x 40:1 extractions	1 x 80:1 extractions	
	($\mu\text{g P g}^{-1}$)	($\mu\text{g P g}^{-1}$)	(as % of 2 x 40:1 total)
High P	39.6	34.8	87.9
Low P	10.9	9.7	89.7

opportunity provided by the double-extraction method. The greater advantage of two extractions under conditions of low extraction efficiency (i.e., at higher water:soil ratios) is similarly explained. The increasing efficiency of P extraction (i.e., $\mu\text{g P g}^{-1} \text{ ml}^{-1}$ water) at lower water:soil ratios suggests that plant P uptake from the soil solution at extremely low ratios may be very efficient, relative to laboratory procedures as used in this experiment.

The small difference in water-extractable P removed by either a single 40:1 or a repeated 20:1 extraction, compared with the greater difference at higher ratios, suggests that at a given soil P status, the total volume of water employed becomes an increasingly important factor determining P desorption as solution:soil ratio decreases. The Langmuir model showed that this relationship also applied as soil P status declines. Consequently, in the field situation it appears that the reported effects of low soil moisture level in limiting plant P uptake (Finn and Mack, 1964) could be due largely to a low level of P desorption into soil solution as well as a corresponding low transfer of P to the plant root (Thomas and Peaslee, 1975).

The amount of DIP was affected little by an increase in extraction period from $\frac{1}{2}$ to 2 hours, although the greatest effect was at higher extraction ratios. Therefore, while P release from a single, compared with 2 successive extractions occupying differing total times have been compared, such differences would not alter the conclusions reached, especially at low solution:soil ratios.

5.3.1.2 Effect of successive extractions with water on desorption of P.

The relationship between DIP release per extraction and cumulative DIP release was similar with differing extraction ratios (with

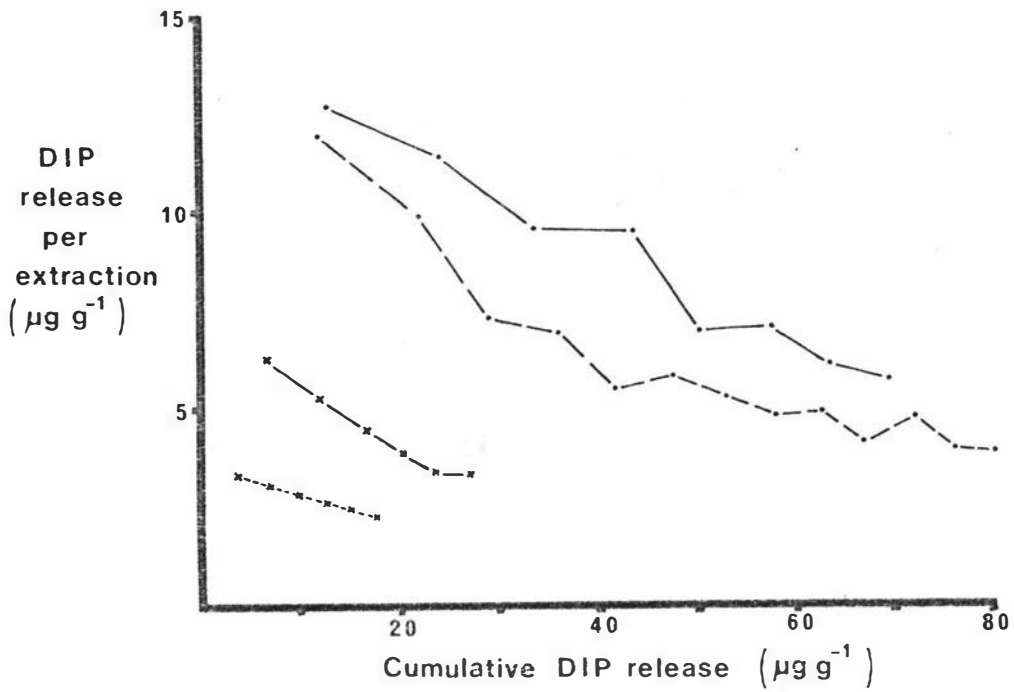


FIGURE 5.2 Relationship between DIP release per extraction and cumulative total DIP release;
 · — · 1-hr extraction at a 40:1 water:soil ratio (north 45° slope soil), · --- · 1/2-hr extraction at a 40:1 ratio (north 45° slope soil), x — x 1/2-hr extraction at 40:1 ratio (north 25° slope soil) and x --- x 1/2-hr extraction at a 20:1 ratio (north 25° slope soil).

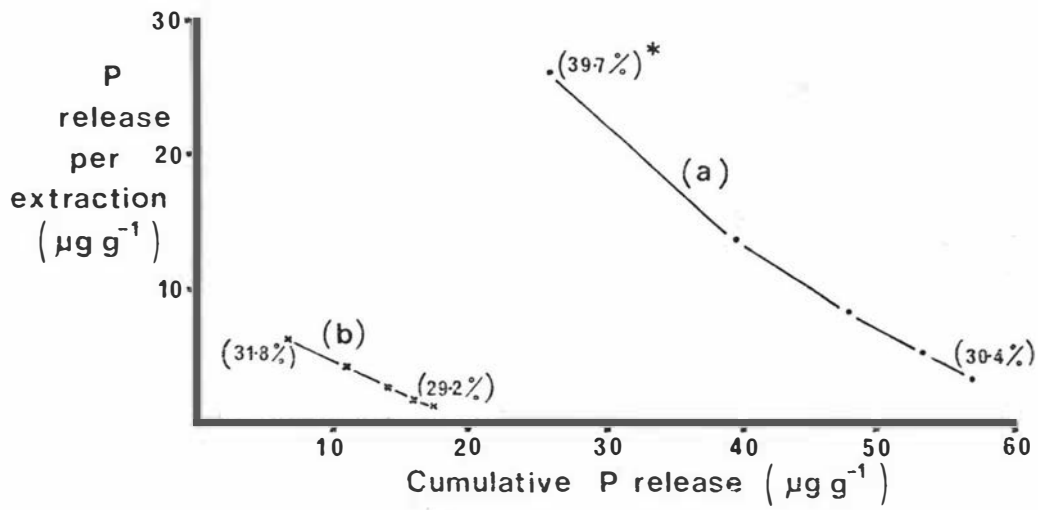


FIGURE 5.3 Relationship between P release per extraction at a 40:1 water:soil ratio (Langmuir model);
 (a) High P soil (initial TP on solid = 65.1µg),
 (b) Low P soil (initial TP on solid = 20.6µg);
 * P release per extraction as a % of the total on the solid prior to extraction.

the North aspect 25° slope soil) and durations (with the North aspect 45° slope soil), as shown in Fig. 5.2. The approximately linear or slightly curvilinear relationship was similar to that displayed by the Langmuir model (Fig. 5.3), indicating that desorbed P was of a slowly released and progressively diminishing form. The almost straight line P exhaustion curve was similar to the lower part of a curve obtained by Shapiro and Fried (1959) in a continuous desorption experiment and also to those presented by Wilson (1968) from similar experiments. From a series of 350 sequential extractions using 10^{-3} N CaCl_2 at a very low ratio with soil (i.e., 3.5ml:5g soil), Peaslee and Balleaux (1977) graphically identified three phases of P release during desorption of previously sorbed P. Inspection of the desorption curves in Figs. 5.2 and 5.3 does not reveal any obvious abrupt changes in desorption rate which would indicate the exhaustion of P in a particular region (Ryden and Syers, 1977). The high water:soil ratio, and therefore the relatively insensitive desorption procedure used, may have obscured such changes.

Ryden et al. (1972) obtained a straight line desorption relationship from repeated extractions of P from an Al horizon soil of a heavily fertilized soil of high pH using 0.1M NaCl as the desorbing solution. This relationship was attributed to the dissolution of dicalcium phosphate dihydrate. The possibility of the dissolution of a discrete-phase fertilizer reaction product significantly contributing to P release in the present laboratory experiments was checked. Solution Ca levels were not sufficiently high for significant dicalcium phosphate dissolution to have occurred.

It is possible that particle breakdown could have contributed towards stabilization of extract P concentration toward the end of the experiments. Ryden (1975), however, noted with several soils that shaking for periods

from 1 to 7 days did not affect subsequent P sorption. It is probable then that particle breakdown did not significantly contribute to P desorption in these experiments.

The similarity between laboratory and Langmuir model results suggests that P release conformed predominantly to that of a single region system in the soil studied. In the Langmuir model P release per extraction decreased successively, both in P content and as a % of the total remaining on the solid phase prior to extraction (i.e., the decline was from 39.7% in the first extraction from the High P soil to 29.2% in the final extraction from the Low P soil, Fig. 5.3). This illustrates a declining efficiency of P release into solution and therefore infers a similarly decreasing availability for plant P uptake as soil P level declines.

5.3.1.3 Effect of antecedent soil moisture content on desorption of P.

The amount of DIP in 6 air-dried soils ranged from $10.7\mu\text{g P g}^{-1}$ in the South aspect 45° slope soil to $77.1\mu\text{g P g}^{-1}$ in the South aspect campsite soil. This represents an approximately 7-fold range in P status (Table 5.2). Despite this range, all soils showed a similar proportional decrease in DIP (Fig. 5.4) when incubated at 90% field capacity (Table 5.2). DIP values after 2 days of incubation ranged from 34.0 to 53.1% of that measured in the air-dried condition. This relatively narrow range in the percentage reduction of DIP suggests that the effect was proportional to soil P status. Continued incubation for 12 days caused a further decline in DIP values for the two soils studied. Following redrying, DIP increased, although after two days the values did not reach the original level.

Sissingh (1969) also demonstrated an effect of antecedent soil moisture on water-extractable P by wetting samples to varying degrees to 13.3% moisture content and incubating for $2\frac{1}{2}$ days. Water-extractable P

Table 5.2 Amounts of total water-extractable P (TDP) in air-dried soil from each stratum of the field trial area and moisture content of each soil during subsequent incubation

	Campsites	25° slopes	45° slopes
<u>TDP from air-dried soil</u> <u>($\mu\text{g P g}^{-1}$)</u>			
North aspect	39.2	14.7	11.7
South aspect	77.1	12.9	10.7
<u>Moisture content at</u> <u>90% field capacity</u> <u>(% by weight)</u>			
North aspect	83.8	66.2	60.0
South aspect	70.0	61.2	55.4

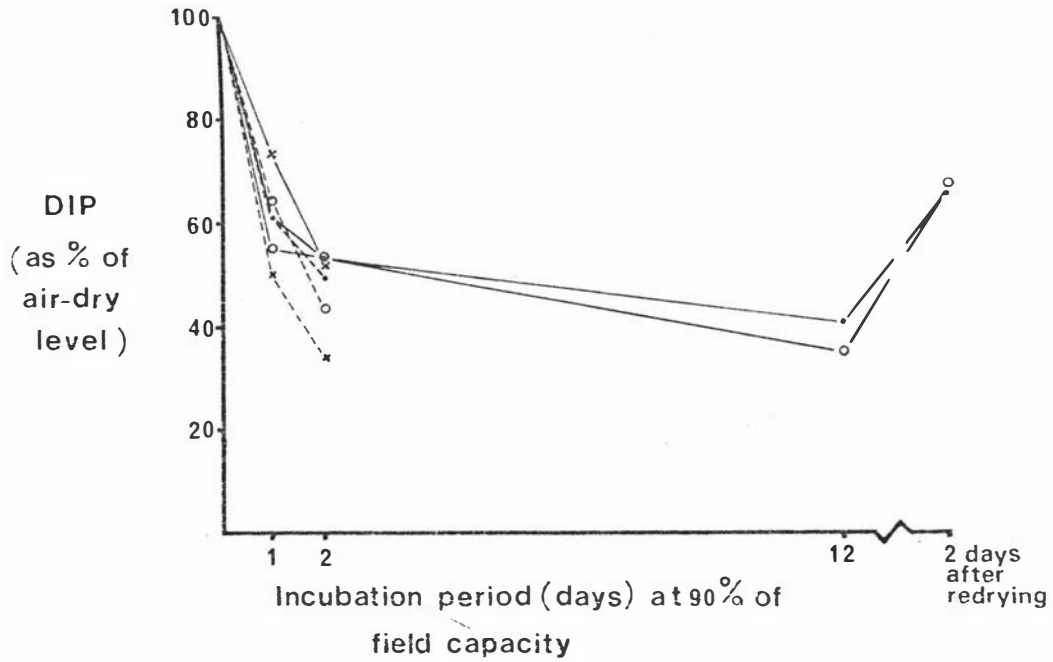


FIGURE 5.4 Effect of antecedent soil moisture on desorption of DIP; · — · north campsite soil, x — x north 25° slope soil, o — o north 45° slope soil, · --- · south campsite soil, x --- x south 25° slope soil and o --- o south 45° slope soil.

declined as previous soil moisture content increased to 6.7% but little additional effect was measured at higher antecedent moisture levels. The effect was greatest in soils containing a high proportion of organic matter. Air-dried soils in the present study contained approximately 5% moisture. The effect of incubating at a much higher moisture content (i.e., 90% of field capacity) in this study was therefore much greater than that observed by Sissingh (1969).

All soils in the present study were of relatively high organic matter content (Table 3.22). Drying may promote mineralization of organic P to inorganic forms, as noted by Barr and Ulrich (1963) during the drying of plant materials. Such forms would be readily water-extractable but could rapidly be immobilized by microbial activity during the warm (approximately 20°C) and moist incubation conditions used in this experiment. Thus, it is possible that changes in the labile organic P levels during incubation were responsible for the measured changes in DIP. However soil DOP, which may have reflected these changes, was not measured in this instance. The exponential decline in DIP, which was rapid during the initial 2 days of incubation and then slower for the following 10 days, could have been due to a gradual conversion of more-physically sorbed P, perhaps initially originating from organic P, to chemisorbed P in region II. This would suggest therefore that the characteristics of incubated soil may even more closely resemble a single-region system than the air-dried soil used in the previous P desorption experiments.

5.3.2 Evaluation of P exchange reactions

5.3.2.1 Fate of applied carrier-free ^{32}P .

After 1½ hours of incubation, the DIP fraction contained only 11% of applied ^{32}P and only 27% of that added was extractable with the Olsen

bicarbonate reagent (Fig. 5.5). This demonstrates an extremely rapid loss of isotopically-exchangeable P into less-readily extractable forms. After $1\frac{1}{2}$ hours, only 64% of the ^{32}P applied was extracted by 1N H_2SO_4 after ignition ("total P") and this proportion did not alter significantly over 24 hours. Fusion with Na_2CO_3 of the residue obtained after ignition and acid extraction showed that the ignition method removed between 1333 and $1430\mu\text{g P g}^{-1}$ i.e., approximately 77% of that measured by Na_2CO_3 fusion (i.e., 1740 to $1850\mu\text{g P g}^{-1}$). Even the Na_2CO_3 fusion method accounted for only 88 to 98% of the total isotope applied suggesting either that some loss of ^{32}P occurred during extraction or, as is perhaps more likely, that errors in counting caused these discrepancies. Dunbar and Baker (1965) also recovered only 90.0 to 91.6% of added ^{32}P associated with the total "active solid phase" P.

The total organic P fraction, calculated as the difference between total "ignition" P and total inorganic P, apparently contained approximately 10% of the added isotope after only $1\frac{1}{2}$ hours of incubation. This increased to about 20% after $6\frac{1}{2}$ hours and remained at this level until 24 hours. It appears highly unlikely that such incorporation into organic forms could have occurred so rapidly, especially in a previously air-dried soil when microbial activity would have been minimal. Later results (Section 5.3.2.2) suggest that a possible build-up of isotopically-exchangeable P in the Olsen-extractable organic P fraction can occur over a longer period (i.e., 2 to 12 days) in a soil that has previously been incubated. It is more probable that not all of the difference in isotope content between total P and total inorganic P fractions is attributable to organic P and that the majority of the difference is due to a change in extractability of inorganic P following ignition (Williams et al., 1970).

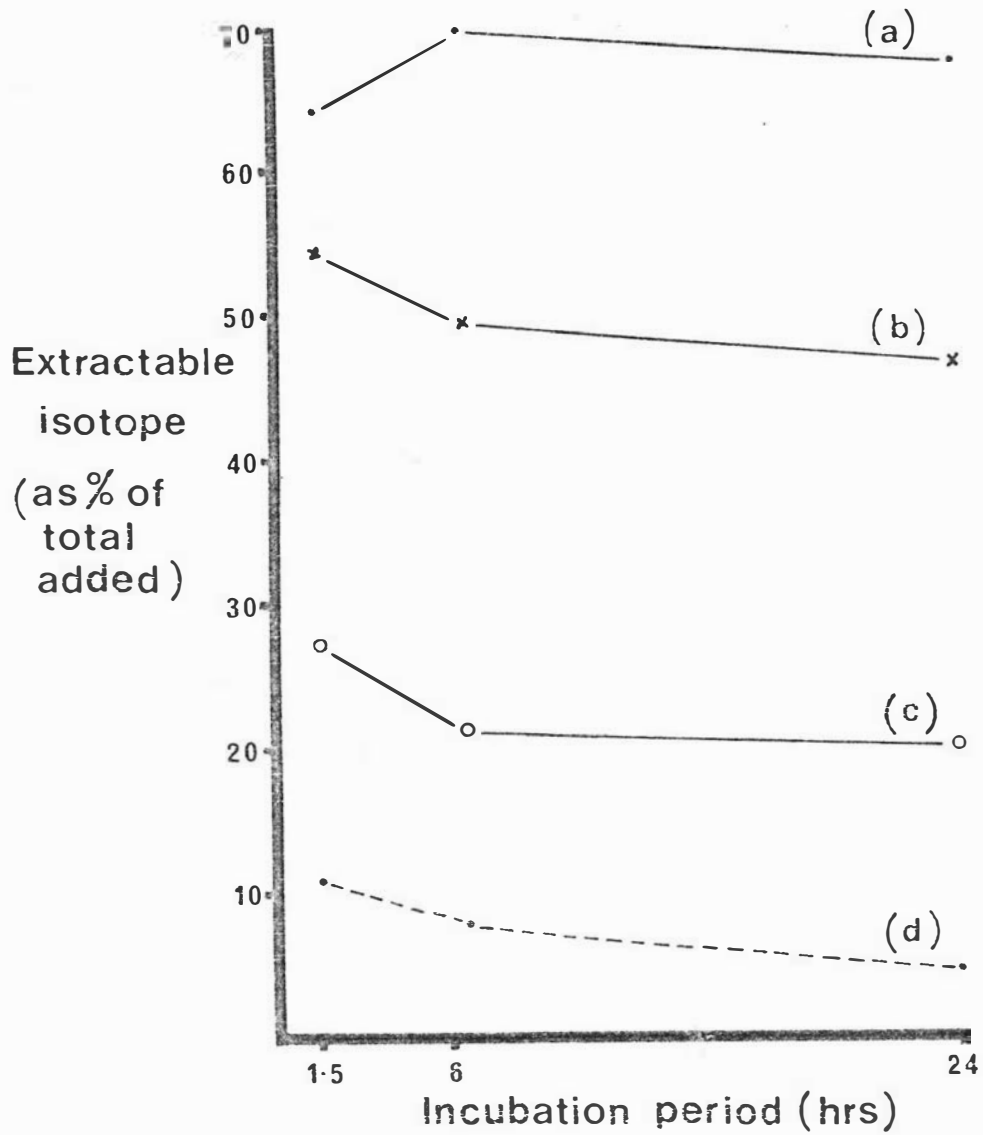


FIGURE 5.5. Fate of carrier-free ^{32}P applied to north 25° slope soil during subsequent incubation; (a) TP by ignition method ($1333\mu\text{g } ^{31}\text{P g}^{-1}$), (b) Total inorganic P by $1\text{N H}_2\text{SO}_4$ soluble ($628.6\mu\text{g } ^{31}\text{P g}^{-1}$), (c) Olsen P ($90.5\mu\text{g } ^{31}\text{P g}^{-1}$), and (d) DIP ($18.1\mu\text{g } ^{31}\text{P g}^{-1}$).

The soil used in this experiment (Waingaro steepland) is classified as a moderately weathered yellow-brown earth (Bruce, 1976). Because of regular superphosphate topdressing, it is of moderately high P status. Given these conditions, it would appear unlikely that incorporation of isotopically-exchangeable P into secondary forms of P not extractable by 1N H₂SO₄, or into the organic P fraction, could account for all of the 20% isotope attributed to be present in organic P. Because 1N H₂SO₄ extraction following ignition markedly underestimated the "total" P level, it would not be unexpected if total inorganic P extracted by 1N H₂SO₄ was also appreciably less than the full amount. Dormaar and Webster (1964) measured incomplete recovery of total P from mineral soil. In addition, they considered that in inorganic soils, combustion was incomplete at temperatures less than 650°C but at higher than 400°C volatilization could occur. Because the soil used in this study had a relatively high organic matter content (approximately 20% by weight), these effects could account for some of the unexpected results described above.

As previously noted, there was an extremely rapid loss of isotopically-exchangeable, water-extractable P following ³²P addition. It is possible that because of the much wider water:soil ratio present than in a moist soil, the extraction procedure facilitated better contact and may have been a major factor promoting net P sorption. This possibility was tested by comparing specific activities of 1:1 and 40:1 water:soil extracts. The respective specific activity levels one hour after isotope addition were 3595 and 3040cpm μg ³¹P⁻¹. This demonstrated that the wider solution:soil ratio was not a factor promoting exceptional isotope sorption. These results support the findings of Barbier et al. (1954) and Mattingly

and Talibudeen (1960) who concluded that varying soil:solution ratio had little effect on the rate of isotopic exchange.

The differences in isotope content between the various forms of P occurred largely within 1½ hours of ^{32}P addition. The subsequent slower decline in ^{32}P content of the DIP, Olsen, and total inorganic P fractions was at a similar rate, indicating that isotopic exchange between these fractions had reached a relative equilibrium. Apart from the slight rise in ignition "total" P isotope content between 1½ and 6 hours of incubation, the same relative equilibrium could also be said to subsequently include the TP fraction. It was therefore apparent that an extremely dynamic equilibrium existed within the soil and that any changes in P content of the more labile fractions would be quickly reflected in at least all inorganic forms of soil P.

5.3.2.2 Effect of soil P status on net sorption of applied carrier-free ^{32}P from soil solution

The South aspect campsite soil, North aspect campsite soil, and North aspect 45° slope soil used in this experiment contained 70.9, 36.0, and 17.0 $\mu\text{g P g}^{-1}$, respectively, of DIP, and 183.7, 104.0, and 40.2 $\mu\text{g P g}^{-1}$, respectively, of Olsen P when analyzed in an air-dry condition.

The proportion of applied ^{32}P which remained either water or Olsen extractable after any incubation period was higher in soils of higher P status, i.e., higher in extracts from the South campsite soil than from the North 45° slope soil (Fig. 5.6). Most of the ^{32}P added to each soil was not water-extractable or Olsen-extractable within 1 hour of application. The proportion of ^{32}P in solution after that time, however, was more related to soil P status. The Langmuir model similarly showed that at equilibrium the High P soil contained the highest proportion of label in solution (Table 5.3).

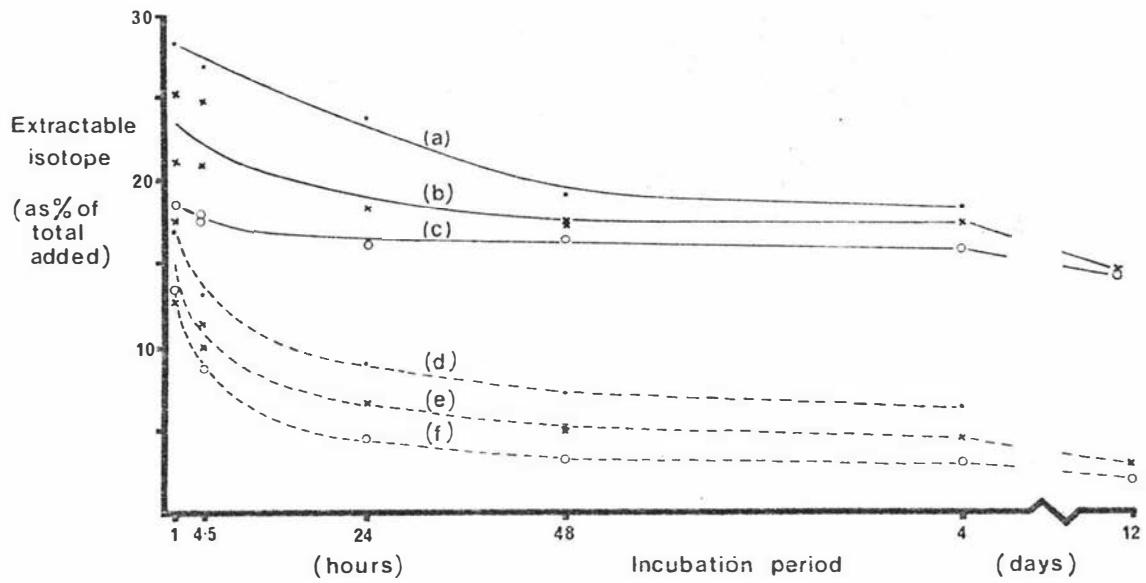


FIGURE 5.6 Change in isotope content during incubation of water and Olsen P extracts from soils of differing P status; (a) Olsen extract, south aspect campsite soil, (b) Olsen extract, north aspect campsite soil, (c) Olsen extract, north aspect 45° slope soil, (d) Water extract (40:1), south aspect campsite soil, (e) Water extract (40:1), north aspect campsite soil, and (f) Water extract (40:1), north aspect 45° slope soil.

Table 5.3 Effect of soil P status on the fate of applied label and the time required to reach equilibrium (Langmuir model)

	<u>High P soil</u>	<u>Low P soil</u>
Equilibrium level of label in solution ($\mu\text{g P g}^{-1} \times 10^{-5}$)	5.34	3.35
Equilibrium level of label on solid ($\mu\text{g P g}^{-1} \times 10^{-3}$)	1.86	2.66
Time required for solution to reach equilibrium (time units)	6.00	4.40

The Langmuir model also indicated that the isotope should also take longer to reach an equilibrium level in a soil of high P status (Table 5.5), i.e., 6.00 time units in the High P soil and 4.40 time units in the Low P soil. This was examined by expressing both isotope and ^{31}P levels in each extract in terms of Relative Specific Activity (RSA). At an equilibrium values for RSA in both DIP and Olsen extracts should be equal. The results in Fig. 5.7 suggest that although equilibrium had occurred in the 45° slope soil after a 48-hour incubation, it was not reached in either of the high P status campsite soils after 96 hours. Also it had not been reached following a 12-day incubation of the North campsite soil. In this respect, the results supported those from the Langmuir model. The greater time required for a High P soil to reach equilibrium is a reflection of the higher proportion of occupied sorption sites on the solid phase. The number of ions in solution striking occupied surface sites, and therefore reflected (as assumed by the Langmuir model) would be higher than in a Low P soil. This would reduce the net sorption rate.

The equilibrium between DIP and Olsen P in the 45° slope soil appeared to stabilise with the Olsen RSA at a slightly higher level than that of water-extractable. While the difference was small, it may have been induced by incorporation of some ^{32}P into bicarbonate-extractable organic forms during this period. If the ^{31}P content of these forms was unmeasured, i.e., no hydrolysis occurred prior to, or during measurement of inorganic P, then the derived RSA values for the Olsen extract would be higher than the true level. Conversely, complete hydrolysis of any organic P present in the Olsen extract (MacLean, 1965; Halm et al., 1972) would lead to an underestimation of RSA. In the 45° slope soil at least, it appears that the net effect is one of Olsen P RSA overestimation relative to the water-extractable RSA value, i.e., some incorporation of ^{32}P into

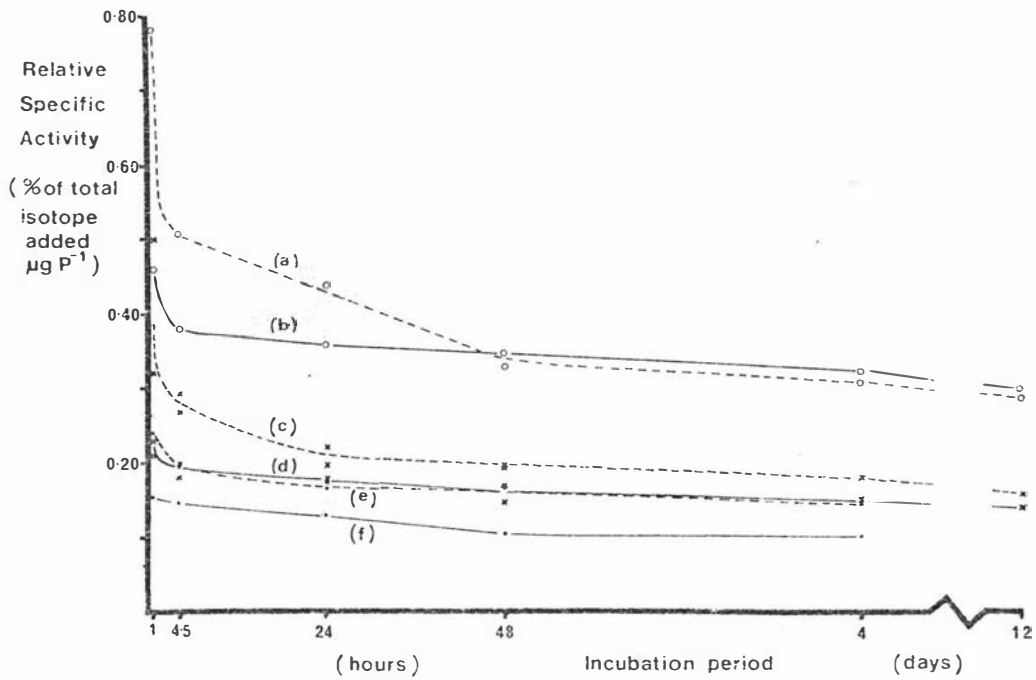


FIGURE 5.7 Change in isotope content (Relative Specific Activity) during incubation of water and Olsen P extracts from soils of differing P status; (a) north aspect 45° slope soil, water extract (40:1), (b) north aspect 45° slope soil, Olsen extract, (c) north aspect campsite soil, water extract (40:1), (d) north aspect campsite soil, Olsen extract, (e) south aspect campsite soil, water extract (40:1) and (f) south aspect campsite soil, Olsen extract.

bicarbonate-extractable organic forms has occurred. This being so, it is also likely that the same occurred in both campsite soils which may therefore be even further from equilibrium than indicated in Fig. 5.7.

The very wide range in P status of the soils used in this experiment had relatively little effect on the proportion of isotope retained in solution by each soil after any incubation period. This indicates that the equilibrium between these labile P forms and less-available forms was similarly little affected by P status, although the RSA values indicate that complete equilibrium between DIP and Olsen-extractable P forms in very high P status soils may have been significantly delayed.

5.3.3 Effects of the addition to soil of P from various sources.

These effects were evaluated by determining both ^{31}P content (as a measure of "apparent" recovery of added P) and ^{32}P content (as a measure of "true" recovery of added P) of water and bicarbonate extracts.

5.3.3.1 Changes in extract ^{31}P content.

All three forms of added P, i.e., from litter, dung, and superphosphate sources, caused an increase in the P content of water and Olsen extracts from both soils. This amount declined sharply in the water extracts over the subsequent 7 days, whereas changes in Olsen P over the same period were more variable (Fig. 5.8). In general, the increase in P level in the extracts reflected the amounts of added inorganic P, being highest for the superphosphate treatment, which received $88.5\mu\text{g}$ inorganic P g^{-1} soil, and lower and similar in the pasture and dung treatments, which both received $79\mu\text{g}$ inorganic P g^{-1} soil.

After 42 days of incubation only a very small proportion of the added P remained in a water-extractable form. Even with the super-

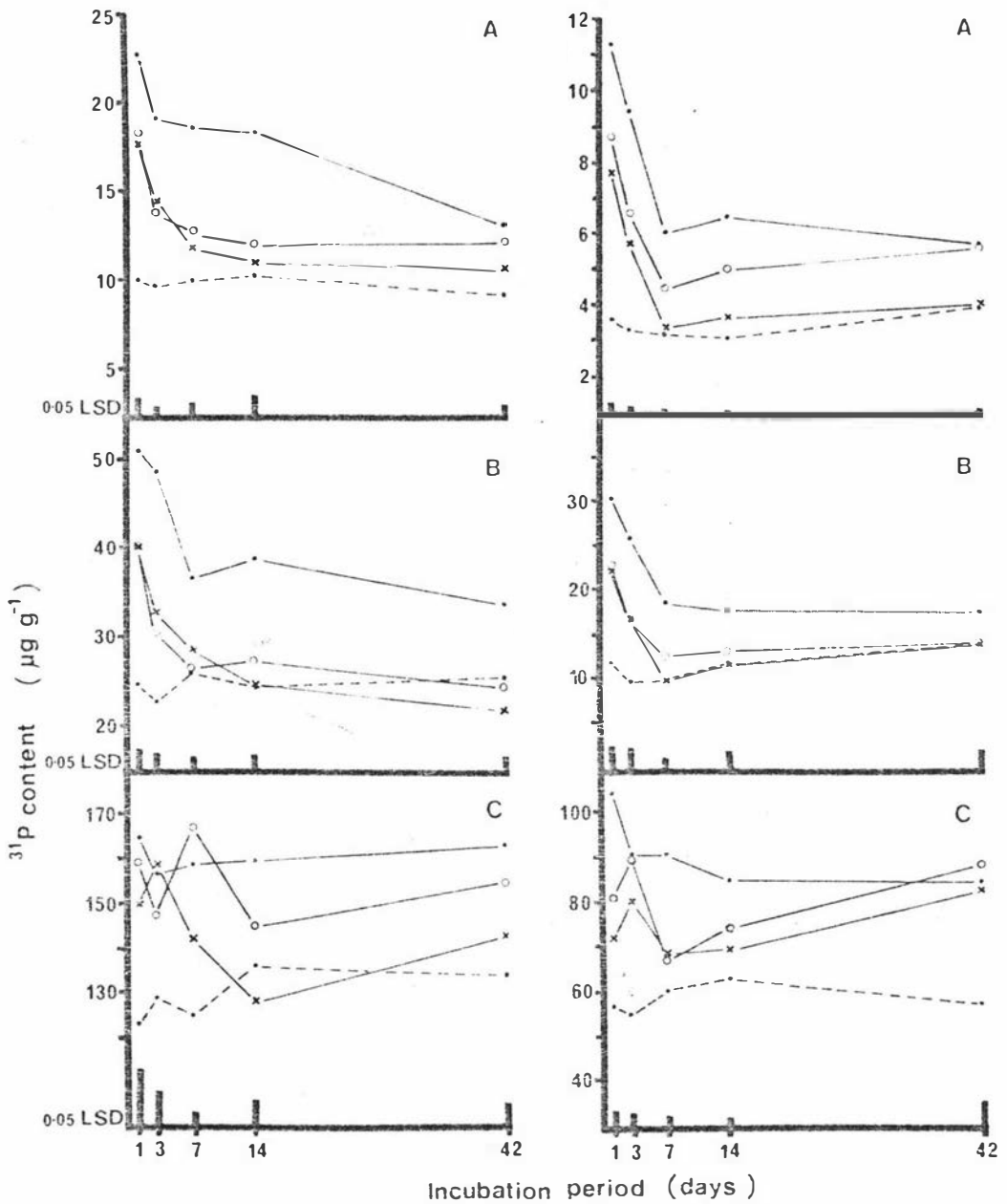


FIGURE 5.8 Change in ^{31}P content of A water-extractable P (10:1 ratio), B water-extractable P (40:1 ratio), and C Olsen P at various times following addition to soil of water-extractable P from superphosphate ($\cdot - \cdot$), litter ($x - x$) dung ($o - o$), and control - nil added P ($\cdot - - \cdot$): left side = north aspect campsite soil and right side = north aspect 45° slope soil.

phosphate treatment the P level in the 40:1 water extract was only 7 μ g and 4 μ g above control (no added P) in the campsite and 45^o slope soils, respectively. The Olsen P levels remained more stable and in the superphosphate treatment were 29 μ g and 24 μ g P above the control, respectively; this still represented only 33 and 27% , respectively, of the added P. The net sorption loss of both water-extractable and Olsen P appeared to be only slightly affected by initial soil P status. The results supported the Langmuir model, however, in that the greatest increases in solution P level were recorded in the soil of higher P status (Table 5.4). Added P from both litter and dung sources appeared to show similar net effects, although the increase in P content of water and Olsen extracts was greater from dung in most cases. This was especially so after 42 days of incubation when the dung P levels were higher than for the litter treatment in all extracts, the difference being not significant ($P \leq 0.05$) in only the TDP extracted at a 40:1 water:soil ratio from the 45^o slope soil.

After 42 days the TDP level (40:1 ratio) in the campsite soil which had received P from litter was significantly ($P \leq 0.05$) less at 21.7 μ g ³¹P g⁻¹ than in the control treatment (25.3 μ g ³¹P g⁻¹), indicating a net immobilization of previously-extractable P. The associated level of TDP extracted at a 10:1 ratio was however higher (i.e., 10.6 compared to 9.2 μ g ³¹P g⁻¹) than the control treatment at this time. That such a situation could arise appears highly unlikely and the difference between the ³¹P levels of the 40:1 water extracts from the litter and control treatments in the North campsite soil was more likely due to experimental error, leading to either an overestimation of the control or an underestimate of the litter treatment value.

Table 5.4 Effect of soil P status on the fate of applied P
(Langmuir model)

Level of added P ($\mu\text{g P}$)	High P soil			Low P soil		
	0	+ 80	+ 120	0	+ 80	+ 120
Total P in solution at equilibrium	74.8	141.9	178.2	10.4	53.7	83.4
Total P on solid at equilibrium	65.1	78.0	81.7	20.6	57.3	67.6

The Olsen P values for the litter and dung treatments varied erratically in both soils over the incubation period, indicating variable net immobilization and mineralization of inorganic and organic P, respectively. The reason for this is unexplained in view of the relatively stable Olsen levels in the superphosphate and control treatments. The fluctuations may have been stimulated by the small amount of organic P or perhaps associated C and N also added in the litter and dung treatments.

After 53 days of incubation, more detailed analysis was undertaken to determine the fate of applied ^{31}P (Table 5.5). Addition of P in all forms induced a rise in 0.1N-NaOH extractable inorganic P levels and in all but one treatment (dung P on 45° slope soil), also a smaller decline in 0.1N NaOH organic P. This effect was greater on the campsite than on the 45° slope soil. The increase in 0.1N NaOH inorganic P in the campsite soil over all treatments ranged from 80 to $103\mu\text{g P g}^{-1}$ and on the 45° slope soil from 33 to $69\mu\text{g P g}^{-1}$. These increases were obviously derived from both added P and the mineralization of 0.1N-NaOH extractable organic P. The net rise above that attributable to mineralized organic P was from 24 to $40\mu\text{g}$ on the campsite and from 19 to $33\mu\text{g}$ on the 45° slope soil and must represent the minimum possible net contributions from added P. These levels of P increase were similar to the rise in Olsen P levels after 42 days of incubation and therefore could have occurred largely within this fraction.

The observed 'priming' effect of added inorganic P in reducing 0.1N NaOH organic P levels has been reported previously (Acquaye, 1963; McCall et al., 1963; Enwezor, 1966; Smith, 1966). The effect was similar in all plus-P treatments and therefore was apparently more related to the inorganic P content of each treatment than to associated organic P, carbon, or nitrogen components associated with water-extractable P from litter and

Table 5.5 Amounts of soil P fractions after 53 days of incubation both with and without addition of water-extractable P from pasture litter, dung, and superphosphate sources ($\mu\text{g P g}^{-1}$)

Treatment	Soil (North aspect only)	0.1N NaOH		Total inorganic P (1N H ₂ SO ₄ extractable)	Total P (Ignition method)	Total organic P (Ignition method)	Total P (Na ₂ CO ₃ fusion method)
		Inorganic	Organic				
Control	Campsite	766	629	1044	1806	762	2160
	45° slope	415	347	526	922	396	1240
Litter P	Campsite	869	566	1120	1897	777	2210
	45° slope	476	295	568	952	384	1280
Dung P	Campsite	851	578	1090	1900	810	2270
	45° slope	448	347	545	932	387	1250
Superphosphate P	Campsite	846	573	1112	1874	762	2330
	45° slope	484	307	575	956	381	1310

dung, which also may have promoted P mineralisation.

As discussed in Section 5.3.2.1 inorganic P extracted by 1N H_2SO_4 appears to represent, in the soils from the field trial area, an incomplete estimate of total inorganic P. The measured increases in the inorganic P level in the campsite soil plus-P treatments, however, were equivalent to a large proportion of the added P. On the 45° slope soil the corresponding P level increases above control were smaller.

Total P measured by Na_2CO_3 fusion was higher in all plus-P treatments than in the control, but the marginal differences were not significant at this level of measurement. The results illustrated further the incomplete measure of total P provided by the ignition method, i.e., equivalent to about 85% and 75% of that measured by Na_2CO_3 fusion on the campsite and 45° slope soils, respectively.

Only minor treatment effects on the total organic P level were measured. These suggested a slight increase in the campsite soil but, conversely, a decrease in the 45° slope soil organic P level. These changes, however, were not significant.

5.3.3.2. Changes in extract ^{32}P content.

The level of ^{32}P in any extract represented the actual added P remaining in solution, as distinct from solution ^{31}P level which included some previously sorbed ^{31}P .

The ^{32}P level in all control treatments (i.e., carrier-free ^{32}P applied) declined throughout the 42-day incubation period, indicating that even after this time ^{32}P in solution had not fully equilibrated with the exchangeable ^{31}P pool (Fig. 5.9). Where ^{32}P was added to soil with ^{31}P (i.e., with either a litter, dung, or superphosphate P extract), variable effects were obtained during subsequent incubation. At the final sampling

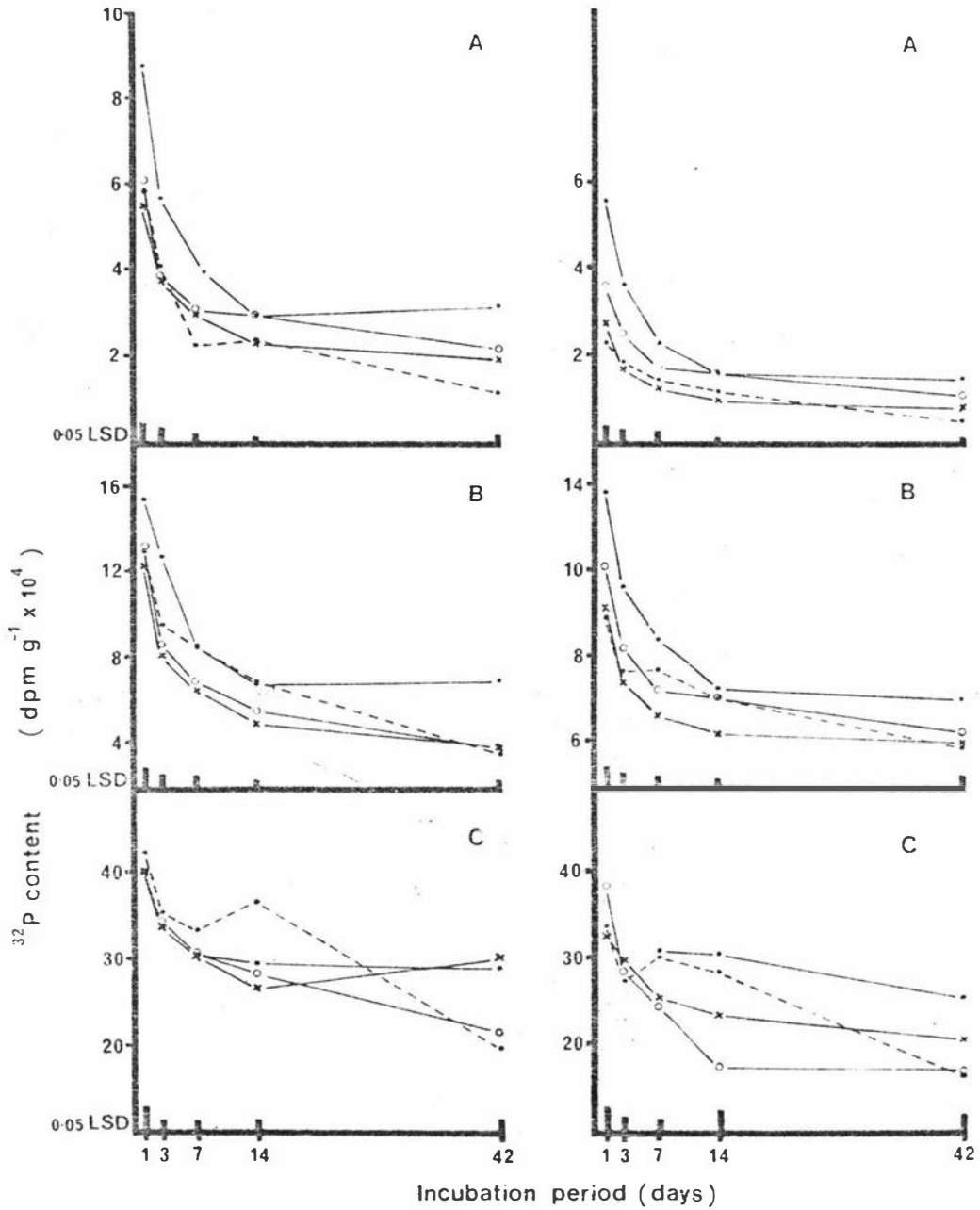


FIGURE 5.9 Change in ^{32}P content of A water-extractable P (10:1 ratio), B water-extractable P (40:1 ratio), and C Olsen P at various times following addition to soil of ^{32}P labelled water-extractable P from superphosphate ($\cdot - \cdot$), litter ($x - x$), dung ($o - o$), and control-carrier free ^{32}P added ($\cdot - - - \cdot$); left side = north aspect campsite soil and right side = north aspect 45° slope soil.

on day 42, however, the ^{32}P content of all extracts from plus-P treatments was higher than from the control, and higher from the campsite soil in all instances. The ^{32}P content of the plus-P treatments (i.e., the level of added P) generally tended to stabilize, after about 14 days. The extent of early downward displacement (i.e., over days 1 to 14) of the plus-P treatment ^{32}P levels in either water or Olsen extracts, relative to control, appeared to be related to the quantity of added P. At the high added P level (e.g., the superphosphate treatment) the ^{32}P in solution tended to remain higher throughout incubation than in the control, especially in the 10:1 water extract. At lower levels of added P, the solution ^{32}P content initially decreased below that of the control before reaching a more stable level. In general, the amount of added P remaining in solution tended to reach an equilibrium after approximately 14 days. The ^{32}P content of the solution at this equilibrium was proportional to the total inorganic P added and also to the P status of the soil, both factors which influenced the ^{31}P content of the soil solution.

5.4 General Discussion

Soil solution P is known to be in dynamic equilibrium with P on the solid phase (Taylor and Gurney, 1962). Both sorption and desorption experiments using soils from the field trial area showed that any disturbance of the solution P concentration resulted in a move toward rapid establishment of a new equilibrium. These effects could be predicted qualitatively by a simple Langmuir model with fixed sorption and desorption rate constants. This suggests that in the soils studied, which were of either moderate P status (from slopes) or high P status (from campsites), P in solution was predominantly related to a solid phase of uniform

sorption and desorption characteristics.

The existence within soils of at least two regions of differing P sorption characteristics has widely been reported (Shapiro and Fried, 1959; Muljadi, 1966; Syers et al., 1973; Ryden and Syers, 1975a). This was confirmed in the present experiments. The rapid loss of carrier-free ^{32}P from solution indicated the presence of a rapidly exchanging and probably loosely-bound form of P. The similar rapid loss of P from even 1N H_2SO_4 -extractable forms, however, demonstrated that considerable sorption had occurred also on sites which were relatively inaccessible for subsequent exchange. These sites may be those associated with the "absorption" process postulated by Ryden (1975) to explain the slow decline in solution isotope content with incubation. It is likely, however, that the rapidly exchanging forms of P will dominate the sorption characteristics of the soil during prolonged incubation.

Soil P levels recorded in Section 3 indicated that region I P sorption sites (Ryden and Syers, 1975a) in these soils were saturated. The continued extraction of P by water, despite several successive desorption cycles, suggested that considerable mobilization of chemisorbed P in region II to more-physically sorbed P had occurred. This continued over a relatively large net P desorption range and in this situation demonstrated the predominant influence of region II characteristics.

Total P desorbed by successive extractions could be regarded as equivalent to that induced by prolonged plant P uptake, e.g., the annual pasture P uptake from 25° slopes was 39.4kg ha^{-1} (Table 3.6). Within a soil depth of 7cm this would be equivalent to P desorption of approximately $70\mu\text{g P g}^{-1}$ per year. Annual plant P uptake would therefore induce an appreciable decrease in solution P concentration if direct contributions to the plant-available pool over the same period from fertilizer, litter,

and dung, and from the mineralization of organic P from various soil or organic residue sources were excluded. The relative significance of fertilizer P contributions, compared with inorganic P from other sources, could only be determined in the field situation from a series of P desorption measurements conducted during a long period when topdressing did not occur.

The significance of solution:soil ratio in affecting desorption was demonstrated by Barrow (1977) using 0.5M NaHCO_3 . It was also inherent in the "capacity factor" derived by Cole et al. (1977), which decreased as solution P concentration increased. The desorption experiments in the present study indicated that solution volume was an increasingly important factor at low soil moisture levels and that the effectiveness of P desorption per unit volume of solution tended to increase as the solution:soil ratio declined. Such results suggest that soil solution P concentrations in field soils may be relatively high compared with those of much wider ratios as used in laboratory experiments.

The primary effect of soil moisture content on plant P uptake will operate through the level of P release into the soil solution. A secondary effect, however, will be the influence of soil moisture content on the rate of P diffusion to the plant root. The factor limiting plant P uptake at a given soil moisture content will depend on both the soil P status as it affects the equilibrium P concentration of the soil solution and the soil texture as it affects the P diffusion coefficient (Olsen and Watanabe, 1963).

The addition to the soil solution of water-extractable P from either litter, dung, or superphosphate sources resulted in a rapid net sorption of P. The almost complete loss of added P from water-extractable forms

after 42 days of incubation displayed a similar relationship to that described by Ryden et al. (1977) as the "relative extractability of added P" (two 40:1 solution:soil ratio extractions of 1 hour each) during subsequent incubation. In the present study, the Olsen 'pool' retained a greater proportion of added P although the real effect on this fraction of added P from litter and dung sources was not clear.

The residual increase in solution P concentration after 42 days of incubation appeared to be relatively unaffected by the source of applied P, but more related to the amount of inorganic P added. It would appear then that water-extractable inorganic P derived from either litter or dung was equally as effective in increasing soil P levels, at least soil TDP levels, as was P from superphosphate. Consequently, it is probable that P from these various sources can be regarded as having a similar plant availability in the soil. In the field situation the relative contributions of P from either litter or dung to plant uptake would seem to be limited primarily by the net rate of inorganic P release and organic P mineralization from these materials as largely affected by temperature (Floate, 1970c), moisture content (Floate, 1970d) and associated microbial activity (Birch, 1961; Ellis, 1974).

In general, the Olsen P measurements were less satisfactory than water-extractable P measurements in reflecting the effects of added P on solution P concentration. This was especially so in the litter and dung treatments, although the reason for this is unexplained. The use of water-extractable P, however, should be combined with a standard sample incubation or preparation procedure. The sharp decline in water-extractable P following the incubation at high moisture content of previously air-dried soils suggests that care is required in defining water-extractable P, and in relating it to other forms of P, or to plant-available P. This would be

particularly so in contrasting seasons when topsoil moisture content may range from near wilting point to greater than field capacity for prolonged periods. Although the effect of intermediate moisture levels was not evaluated, it appears that some pre-incubation would be desirable where results are to be related to field conditions.

SECTION 6

CHARACTERIZATION OF SHORT-TERM, PLANT-AVAILABLE P
USING A DOUBLE LABELLING TECHNIQUE

6.1 Introduction

Plant P requirements may be considered either over a short term (i.e., available over a period of days) or as that potentially available over a year or more. Assessments of available P are generally related to plant uptake over a prolonged period, i.e., they include a measure of the capacity of the soil to supply P. Such estimates have been obtained by calculating the levels of isotopically-exchangeable P, as with the L value (Larsen, 1950) and A value (Fried and Dean, 1952a) techniques or by empirical methods using either water (van der Paauw, 1971), acid (Truog, 1930), or alkaline (Olsen et al., 1954) extractants. Any such estimates are involved primarily with P on the solid phase and do not attempt to measure P in solution, i.e., that immediately available to plants. The determination of plant P uptake over short periods of time is difficult because of the small quantities involved. The measurement of this pool of highly available soil P would establish a non-empirical reference point to which more exhaustive and empirical soil test procedures could be related. This would permit examination of the relationship between plant uptake of P and that within any defined "pool" in the soil and thus how this relationship may vary with different soils and differing plant species.

A technique was developed to characterize soil P taken up by plants over a short period of time. This was evaluated using two soils of differing P status and using ryegrass and white clover. Plant P uptake was compared with the amounts of both water- and bicarbonate-extractable P in the soils.

6.2 Materials and Methods

The technique used to evaluate "short-term" plant-available P involved the use of both ^{32}P and ^{33}P . A growing plant was placed in contact with soil that had been incubated with carrier-free ^{33}P for a relatively long period and subsequently also with ^{32}P for a short period. Consequently, plant P uptake over a given period involved ^{32}P and ^{33}P in a certain ratio. This ratio was related to that in different soil extracts.

6.2.1 Preparation of plants

Both ryegrass (*Lolium perenne*; Grasslands "Nui") and white clover (*Trifolium repens*; Grasslands "Huia") were used.

The technique employed was that developed by Stanford and de Ment (1957). A small (300ml) plastic tub with the bottom removed was placed within a similar complete tub and filled three-quarters with clean sand. Approximately 20 seeds were sown on the surface, which was covered and watered. Following germination the seedlings were watered daily and maintained at a temperature of $20^{\circ} \pm 4^{\circ}\text{C}$. Twice weekly, a complete nutrient solution, including P (Middleton and Toxopeus, 1973) was applied at a rate of 30ml per pot. After 2-3 weeks, when approximately 1g of pasture dry matter was produced, the nutrient supply was reduced to one application per week for a further 2 weeks. Clover was not inoculated but adequately supplied with nitrogen from the nutrient solution. By this time plant roots were well developed, having explored the full depth of sand (Plate 6.1) and were ready for placing in contact with isotope-labelled soil.



Plate 6.1 Ryegrass grown in sand within nested pots (left side) and showing root development (centre) prior to placement in contact with isotope-labelled and incubated soil (right side).

6.2.2 Preparation of soil

The soils used were from 0-7cm depth from the North aspect campsite and 45° slope strata (Section 3). They were air-dried and passed through a 2-mm sieve.

Air-dry soil (30g) was placed in a 300-ml plastic tub, as used to grow the plants, and carrier-free ^{33}P added ($0.78\mu\text{Ci g}^{-1}$ soil) in sufficient water to reach field capacity. This was mixed thoroughly and incubated for 27 days at approximately 60% field capacity. On day 27, carrier-free ^{32}P was added ($0.3\mu\text{Ci g}^{-1}$ soil), mixed, and allowed to stand until day 30 ready for "before-plant" sampling and placement of plants.

The above incubation periods were selected from previous studies (Section 5) for the following reasons. The ^{33}P was allowed to incubate for as long as conveniently possible, to enable equilibration with the more readily-extractable inorganic soil P. A three-day ^{32}P incubation period was chosen as the time required for the initial rapid decline in total isotope level to have ceased, so that the subsequent rate of change was relatively slow.

Because the ^{32}P had not equilibrated with soil P to the same extent as ^{33}P , the $^{32}\text{P}:^{33}\text{P}$ ratio was higher in the most labile soil P pools. Ideally, this ratio should be stable over the period of plant P uptake.

6.2.3 Sampling and analysis procedures

6.2.3.1 Soil analysis

Soil samples were taken both before (day 30) and after (day 35) plant P uptake to measure any changes in isotope ratio occurring in the soil extracts over this period.

Soil (2g per sample) was analyzed for water-extractable P content

(both at 10:1 and 40:1 water:soil ratios) and for Olsen P, as outlined in Section 5.2.1.3. Total ^{32}P and ^{33}P activities (dpm) were measured simultaneously using discriminator channel settings of 30-710 for ^{33}P and 750-1000 for ^{32}P (at a Gain setting of 490). Automatic quench control was used to minimize overlap of counts into the adjacent channel setting range. The counting efficiencies of both isotopes in any extract and the carry over of ^{32}P into the ^{33}P channel were determined by adding known ^{32}P and ^{33}P standards to unlabelled samples of the appropriate extracts. An example of the effect of extract type on counting efficiency is shown in Appendix VII.

6.2.3.2 Plant sampling and analysis

On day 30 the bottomless tub containing grass or clover was separated from the lower whole tub. Any compacted roots protruding from the bottom of the sand were loosened and the tub placed within the tub containing isotope-'labelled' soil. These were pressed firmly together to ensure maximum root:soil contact and left for 5 days.

Prior to plant placement, the soil in the lower tub was wetted to field capacity and the sand in the upper tub containing the growing plants was allowed to dry more than previously. This was found to encourage maximum rate of root penetration into the soil following contact. Over the plant contact period, small amounts of additional water were supplied between the rims of the nested tubs. This rewetted the soil but not the surface sand.

Previous pilot experiments showed that appreciable P isotope uptake occurred in grasses after 2 days and that this level was highest from soil of high P status. This was usually, but not always, associated with extensive root penetration into the labelled soil. With clover, however,

root exploration of the soil was much slower and therefore a 5-day contact period was chosen for both species.

On day 35 all top growth was harvested from each pot, oven dried overnight at 60°C, and finely ground in a forced draught chamber. Total ^{31}P content was measured as described in Section 3.2.4.3 and both ^{32}P and ^{33}P activity measured as for soil extracts.

6.3 Results and Discussion

6.3.1 Soil ^{31}P levels

There was no significant difference in either water-extractable or Olsen ^{31}P levels between each of the soils used for clover or ryegrass P uptake (Table 6.1). This was the case for both campsite and 45° slope soils. Whereas the soil P levels after plant P uptake in each case showed a small decline from the "before plant" level, this was not statistically significant. Some of the difference could be attributed to P removal by the plant over 5 days but this would have been a very small amount. It is likely that the measured lower levels were caused by some contamination of the soil with sand. Soil was collected after inverting the tubs so that the soil rested on the sand used to initially grow each plant. The network of roots present, especially grass roots, made soil collection difficult and some soil samples did contain a small amount of sand. This would have diluted the soil sample with some consequent reduction in measured P concentration. Because of the long incubation period prior to plant placement it is unlikely that any marked decline in water-extractable P values occurred during plant P uptake as was shown to occur during a 2-day incubation period (Section 5.3.1.3).

Table 6.1 Soil P levels before plant P uptake and soil and plant P levels after plant P uptake ($\mu\text{g P g}^{-1}$)

Soil	Treatment	Soil P				Plant P		
		Before plant P uptake		After plant P uptake				
		Water-extractable P		Olsen P				
		10:1	40:1	10:1	40:1			
North Campsite	White clover	10.0	27.2	165.6	9.2	22.6	156.3	960
	Ryegrass	10.7	29.0	173.5	8.7	22.0	173.0	1230
North 45° slope	White clover	5.0	15.3	76.3	4.5	15.0	74.4	790
	Ryegrass	4.9	16.7	73.2	4.8	14.6	78.1	1150

6.3.2 Plant ^{31}P levels

The P concentration of both the white clover and ryegrass ranged from 790 to 1230 $\mu\text{g P g}^{-1}$ and were therefore considered to be at a deficient level (McNaught, 1970). This was so even though both species appeared to be in a healthy condition during the experiment. Both ryegrass and white clover were treated similarly in all respects and therefore it could be expected that the P concentration levels in each were similar before being placed in contact with soil. It is possible, however, that because of a less intensive root system white clover suffered with respect to P uptake and may have contained less P at the start of the experiment. Nevertheless, the P levels within either the grasses or clovers would have initially been similar. The measured different plant P levels with the two soils, induced over a 5-day uptake period, were therefore directly due to different levels of available soil P. The P concentration in ryegrass on the 45° slope soil was only slightly lower than that on the campsite soil, reflecting the relatively efficient exploratory ability of grass roots. This contrasts with the greater difference between clover P levels on the different soils, a reflection of the dependence of clover on a higher soil P status because of its less extensive root system.

The very low plant P levels obviously induced rapid P uptake from each soil; a factor necessary for the attainment of measureable isotope levels over a short experimental period.

6.3.3 Soil and plant ^{32}P and ^{33}P ratios

The expression of the P uptake by plants from soil and the P content of each soil extract in terms of a component isotope ratio provided a

distinctive means of characterization. The $^{32}\text{P}:^{33}\text{P}$ ratio of the water-extractable P was always higher than that of Olsen P (Table 6.2). This would be expected because it is a reflection of the Relative Specific Activity (RSA) values measured in Section 5, except that in this experiment, ^{33}P has effectively replaced ^{31}P as the denominator in the ratio.

A comparison of "before" and "after" isotope ratios in each soil extract shows that there was a change during the 5-day period allowed for plant uptake. This change was most marked in the campsite soil.

It is likely that the greatest uptake of P in this experiment would have occurred in the latter part of the 5-day contact period as root:soil contact rapidly improved. Consequently, it follows that the plant isotope ratio should be more similar to the "after" than the "before" soil isotope ratio. Because the ratio declined during the experiment, a mean value from "before" and "after" ratios would slightly over-estimate the mean ratio of the ^{32}P and ^{33}P , taken up by the plant. For campsite soil growing clover, the calculated mean ratios for 10:1 and 40:1 water-extractable P after plant growth were 0.866 and 0.959, respectively. In the corresponding system with grass, the relative isotope ratios were 0.891 and 0.922. The mean ratio in both cases was slightly higher in the 40:1 than in the 10:1 water extract suggesting that this P pool was closer to that available to the plant. In no extract, however, did this 'over-estimated' mean ratio exceed that in either the clover or ryegrass. It therefore follows that each plant species must have obtained P from a more labile fraction than represented by either 10:1 or 40:1 water extractable P. The difference, however, was not as great as occurred in the 45° slope soil where the isotope ratio of plant P uptake was higher than in all soil P extracts, both before and after plant contact. It appears that at lower soil P status, plant-available P was even less well represented by that extractable

Table 6.2 $^{32}\text{P}:$ ^{33}P ratios in soil before plant P uptake and in soil and plant material after plant P uptake ($^{32}\text{P}_{\text{cpm}}:$ $^{33}\text{P}_{\text{cpm}}$)

Soil	Extraction	White clover		Ryegrass	
		Before	After	Before	After
North campsite	Water, 10:1	1.020 bB*	0.712 bB	1.054 abAB	0.728 bB
	„ 40:1	1.181 aA	0.737 bB	1.104 aA	0.739 bB
	Olsen	0.497 cC	0.481 cC	0.460 cC	0.444 cC
	Plant	bB	0.970 aA	bB	0.971 aA
45° slope	Water, 10:1	0.781 bA	0.641 bB	0.875 cC	0.524 cC
	„ 40:1	0.744 bA	0.641 bB	0.954 bB	0.612 bB
	Olsen	0.510 cB	0.512 bB	0.537 dD	0.468 dD
	Plant	aA	1.016 aA	aA	1.051 aA

* Duncan's lettering (Duncan, 1955). Common small letters are not significantly different at 5% level of probability; capital letters at the 1% level of probability.

Differences examined within each soil either before or after plant uptake.

at either 10:1 or 40:1 water:soil ratios.

6.4 General Discussion

The isotope ratio technique provided a very useful means of characterizing immediately plant-available soil P. The technique required only sufficient uptake of P to allow measurement of the associated isotope activity. In both the campsite and 45° slope soils this was obtained in two days with ryegrass. With soils of lower P status or a plant species exhibiting less rapid root expansion (e.g., white clover), a longer period is required.

As indicated by the relatively high plant isotope ratio, the immediately plant-available P comprised a more labile fraction than that measured by any extract. For the campsite soil of very high P status, this was most similar to that extractable in water, either at a 10:1 or a 40:1 extraction ratio.

On the 45° slope soil, however, water-extractable P obviously represented a larger 'pool' than that explored by the plant, i.e., the lower mean isotope ratio in the water extracts suggests that an overall less labile fraction of P was extracted by water. This indicates that water-extractable P from the 45° slope soil (of moderate P status) comprised a more heterogenous fraction than that extracted by water from the campsite soil (of high P status). This was not reflected in any higher isotope ratio in the 10:1 than in the 40:1 water extracts from the 45° slope soil, however, as might be expected from the difference in ^{31}P levels of the extracts. The 10:1 water-extractable P fraction, therefore, would appear to constitute merely a small proportion (about 1/3) of water-extractable P obtained in the 40:1 extract.

The significantly higher isotope ratio recorded in the 40:1 compared with the 10:1 water extract from the 45° slope soil, both before and after P uptake by grass, cannot be explained. No such difference was measured in the corresponding 'clover' treatment.

It must be concluded that while both the 10:1 and 40:1 water-extractable P pools were overall isotopically uniform, the plant P uptake occurred from only the most labile component, extracting a form of P that had not participated in exchange to the same extent as that comprising the greater part of the total water-extractable fraction.

In a pilot experiment using a 1:1 water:soil ratio, the P extracted was equivalent to approximately 3.3% of that obtained at a 40:1 ratio or 10% of that at a 10:1 ratio. During plant P uptake the soil was at a condition approximating field capacity (i.e., 93% by weight for campsite soil and 67% for the 45° slope soil). The actual P in solution over the P uptake period, therefore, would have represented less than 10% of that extracted by a 10:1 water extract. It is possible, therefore, that a significant difference in isotope ratio could exist between this fraction, directly available to the plant, and that weakly sorbed by the solid phase but extractable at a wider water:soil ratio.

The same situation applied with the campsite soil, although the plant isotope ratio was more similar to that in the water extracts from this soil, than from the 45° slope soil. This could be expected both from consideration of the slightly higher water:soil ratio of this soil at field capacity, therefore representing a marginally greater proportion of the water-extractable P, and also from the greater ³¹P uptake by plants from the campsite soil which would have promoted slightly greater desorption of solid phase P than occurred in the 45° slope soil.

There appeared to be no difference between ryegrass and white clover

in the form of P utilized, as defined by their isotope ratios under the experimental conditions used. Therefore, the higher ^{31}P status of the ryegrass could only be attributed to a more efficient root distribution in each soil. This reflected a better ability of ryegrass than white clover to rapidly develop root growth and explore new zones of higher P availability. These conclusions are in agreement with those of Nye and Foster (1958) who considered that differences in P uptake by various species was due to differences in root numbers and root tips rather than to any other factor. The results also support those of Mouat and Walker (1959) and Jackman and Mouat (1972) who also concluded that the intensity of root network was the major factor in the greater competitive ability of some species for P. The apparently faster root development by ryegrass than white clover in this experiment suggests that root interception ability could be significant in species establishment, particularly in soils of relatively low P status.

In this context root interception ability will be of more importance in plant P uptake than when plants are well established, where this factor may be regarded as of less significance (Lewis and Quirk, 1967a).

Because plant P uptake occurs from both the soil solution and P weakly held on the solid phase it would be expected that water-extractable P will be similar in isotope ratio to that utilized by plants. Although this was essentially correct, the results suggested that water-extractable P provided a less accurate representation of directly-available P as soil P status declined. It would be expected, however, that plant P uptake over a period longer than 5 days, as used in this experiment, would relate more closely to water-extractable P. The relationship of "more-physically" sorbed P (as defined by Ryden and Syers, 1977, i.e., P equivalent to that removed by two successive 1-hour extractions at a 40:1 water:soil ratio)

to that directly available for plant P uptake is unknown. Unless the isotope ratio of the second 40:1 extract was markedly less than that of the first extract (Table 6.2), then it could be expected that "more-physically sorbed P" may closely resemble short-term plant-available P.

Water-extractable P was a considerably better index of directly plant-available P than was Olsen P. This conclusion supplements the results of Luscombe (1976) who derived a better relationship between the dry matter yield response of ryegrass and water-extractable P than with either Olsen or Truog P values. The isotope ratio results also support the results obtained by Rennes (1978) who found that while both water-extractable P and plant P uptake values declined with time following P application, Olsen P values remained essentially constant over the same period. All of these results demonstrated the relative insensitivity of Olsen P to short-term uptake of P by plants. The relevance of Olsen P to that which is plant-available over a long term may best be determined by establishing the relationship with water-extractable P. A fixed relationship over a range of soils would provide non-empirical support for its use as an index of plant-available soil P. The use of water-extractable P in conjunction with a procedure which predicts the longer-term supply of P may be the best approach toward providing a measure of both "intensity" and "capacity" factors of P supply, considered to be desirable components of a soil P test (Thomas and Peaslee, 1975) which will relate to plant available P.

SECTION 7

SIMULATION OF "ABOVE-GROUND COMPONENTS
OF THE P CYCLE IN STEEP, GRAZED PASTURE

7.1 Introduction

Although in an intensively-grazed pastoral system, the greatest proportion of total P in the P cycle at any one time is contained in the soil, it is the "above-ground" components of the P cycle that appear to have the greatest effect on the efficiency of the cycle (Karlovsky, 1975). Also it is with the above-ground components of the P cycle that the greatest scope for manipulation exists. Results from Section 3 demonstrate, that in grazed hill pastures, topography has a major influence on the quantity of dung returned to different sites and therefore on the efficiency of the P cycle in this situation. The disruption of the P cycle on very steep slopes was such that net transfer losses could account for the greater part of P annually applied as "maintenance" phosphate topdressing. It was suggested in Section 3.3.2.1 that the level of grazing and camping pressure on each topographic stratum within a paddock may also be affected by the proportion of the paddock occupied by the stratum. In paddocks which were relatively steep, therefore, the concentration of dung on all strata could be relatively greater than in less steep paddocks. Other factors which may be considered likely to influence the net P balance on each stratum are the level of pasture production and P content of the pasture, both of which directly affect P uptake from the soil, and also the level of pasture utilization and therefore the proportion of P uptake that is returned to the soil as dung.

In order to examine the effect of variation in some of these factors, and to possibly extrapolate the results of the field trial to other

situations, a mathematical model of the "above-ground" components of the P cycle was constructed. This was based on data from the north aspect paddock and developed to simulate P uptake and return, and consequently the net P balance on each stratum over a period of one year.

7.2 Materials and Methods

The "above-ground" model as described in Appendix VIII was constructed using the following assumptions:

1. Pasture on all strata was of the same mean P concentration.
2. A single stock unit was considered to require 550kg DM yr^{-1} .
3. Stock preferentially grazed strata in the order: campsites > 25° slopes > 45° slopes. The view that animals preferentially graze easier slopes is widely accepted and confirmed by Suckling (1975) who reported accumulation of rank pasture on steeper and lower slopes even at relatively high stocking rates.
4. 55% of total dung return was deposited on campsites and tracks during camping only, and the remainder was distributed in proportion to pasture utilization on each stratum, with the following exceptions: (a) Dung return to 45° slopes was, because of surface steepness, considered to be disproportionately low relative to pasture utilization levels. Most of the grazing of pasture on 45° slopes would be done by stock standing on adjacent tracks. Therefore only 50% of the dung returned to 45° slopes during grazing was considered to remain there. The other 50% was attributed to tracks (and therefore also to campsites). (b) Where a very high concentration of dung accumulated on campsites, it was considered that there was an associated greater

return of dung to adjacent slopes. Consequently, where dung return exceeded 100kg P ha^{-1} , 10% of the surplus was allocated to 25° slopes.

5. 10% of P intake by animals was lost from the grazing area in animal products.

This model was operated incorporating parameters for paddock topography, pasture dry matter production, pasture P content, and pasture utilization similar to those measured on the north aspect paddock (Section 3). As a validation test the appropriate data for the more steep south aspect paddock were substituted and the model re-run.

These effects were evaluated in two model paddocks of contrasting topography; a moderately-steep paddock similar to the north aspect paddock of the field trial (20% of the paddock in campsites, 55% in 25° slopes, and 25% in 45° slopes) and a steep paddock (10% in campsites, 30% in 25° slopes and 60% in 45° slopes), in order to assess if any modifying influence of paddock topographic composition occurs, as was suggested in Section 3.3.2.1. Such a comparison could not be clearly made using the field trial results because pasture production on similar strata differed between aspects. In the "model", however, pasture production on a particular stratum was the same in both paddocks.

The following manipulations of the model were examined:

7.2.1 Effect of stocking rate on the net P balance in each stratum

The maximum stocking rate on the moderately steep paddock was 12.2 stock units ha^{-1} and on the steep paddock 10.2 stock units ha^{-1} . Pasture utilization by grazing animals on each stratum at these stocking levels was considered to be 75, 85, and 70% of available pasture on campsites,

25° slopes, and 45° slopes, respectively which would represent near maximum obtainable on these strata (Section 3). In each paddock pasture production was 11,000, 8,500, and 5,500 on campsites, 25° slopes, and 45° slopes, respectively, with a common P content of 4,500 µg g⁻¹. The effect of lowering stocking rate to half the maximum while still maintaining high utilization levels on campsites and 25° slopes was examined. This simulated a situation where poor pasture control was achieved on steep slopes with perhaps associated ingress of unpalatable weed species, and subsequent grazing pressure on camps and easier slopes was still high, but at a reduced overall stocking for the paddock as a whole.

7.2.2 Effect of overall pasture utilization level on the net P balance on each stratum

Pasture utilization in most large hill paddocks would generally be lower than the high level set in Section 7.2.1, particularly on steep slopes. The effect of lower utilization levels, i.e., 65, 70, and 55% on campsites, 25° slopes, and 45° slopes, respectively, on the net P balance on each stratum was therefore examined. These levels represented an overall average pasture utilization level of 65 and 63% for the moderately steep and steep paddocks, respectively. These levels could be similar to that obtained by many hill farmers.

7.2.3 Effect of pasture production level on the net P balance on each stratum

In order to evaluate the effect of dry matter production alone on the net P balance the annual pasture growth on each stratum was considered to decrease by 20% from those levels described in Section 7.2.1. i.e., to 8,800 kg DM ha⁻¹ on campsites, 6,800 kg DM ha⁻¹ on 25° slopes and

4,400 kg DM ha⁻¹ on 45° slopes. The pasture P content was maintained at 4,500µg g⁻¹. Utilization of this pasture was at the high levels set in Section 7.2.1. This situation simulates conditions where annual pasture growth is limited, perhaps by climatic conditions, but because of a relative shortage of pasture, utilization levels are high.

7.2.4 Effect of pasture P content on the net P balance on each stratum

In order to determine the effect of pasture P content alone on the net P balance on each stratum the P concentration was reduced from 4,500µg g⁻¹ to 3,500µg g⁻¹ while maintaining the production and utilization levels set in Section 7.2.1. This simulates a condition where higher than adequate pasture P concentrations are allowed to decline to a lower level which is not associated with reduced pasture growth, perhaps resulting from a reduced fertilizer input after earlier higher rates associated with a pasture improvement programme.

7.3 Results and Discussion

7.3.1 Model validation

The net P balance for each stratum on the north aspect (Table 7.1), as derived by the model, demonstrated that the assumptions made for the model were realistic in relation to the field situation. By using the same model, and incorporating values for relevant parameters from the south aspect, a net P balance was similarly derived for all strata on the south aspect (Table 7.1). The model slightly over-estimated the net P loss from the south aspect 25° stratum, relative to field results, but otherwise provided an estimate of P transfer remarkably close to that

Table 7.1 Simulated P uptake and return in paddocks on north- and south-facing aspects (Section 3) incorporating parameter values measured in the field

	North			South		
	Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
Distribution of strata (% of total area)	20	55	25	10	45	45
Pasture production (kg ha ⁻¹)	11140	8600	5400	12500	7000	4500
Maximum pasture utilization (% of total available)	80	85	75	75	85	80
Pasture P concentration (µg g ⁻¹)	4500	4500	4500	4500	4500	4500
Stocking rate (S.U. ha ⁻¹)	12.2	12.2	12.2	9.5	9.5	9.5
Pasture P uptake (kg ha ⁻¹)	50.1	38.7	24.3	56.2	31.5	20.2
Litter P return (kg ha ⁻¹)	10.0	5.8	6.1	14.0	4.7	4.0
Dung P return (kg ha ⁻¹)	110.4	10.7	3.6	164.8	11.9	1.5
Net P transfer (kg ha ⁻¹)	+ 65.3	- 17.8	- 14.1	+ 116.8	- 13.7	- 12.7
Measured P transfer (from Table 3.2) (kg ha ⁻¹)	+ 60.7	- 19.5	- 15.4	+ 119.8	- 10.0	- 13.8

measured in the field. The lower measured net P transfer loss from 25° slopes, than that estimated by the model, may have been due to an even greater P return to south aspect 25° slopes in dung than to north aspect 25° slopes, i.e., the model appeared to have underestimated the "spill-over" effect of dung from campsites to 25° slopes at the higher level of dung return to campsites, which occurred on the south aspect.

The generally close simulation of net P transfer on the three south-aspect strata was taken as evidence that the model was sufficiently realistic to be useful in evaluating the effects of other treatments on P uptake and return to each stratum.

7.3.2 Model manipulations

7.3.2.1 Effect of stocking rate on the net P balance on each stratum.

Reducing the stocking rate by half had the effect of withdrawing grazing pressure completely from 45° slopes in both paddocks (Table 7.2). Consequently, net P losses from these areas were nil. Conversely, pasture on campsites was still utilized to the maximum. The lower total stock numbers, however, contributed less dung to campsites and therefore the net P surplus was equivalent to 1/3 or less of that at the maximum stocking rate. The effects on 25° slopes reflected the relative proportion that this slope group occupied of each paddock. In the steep paddock the 25° slopes occupied only 30% of paddock area and therefore grazing pressure and net P losses were higher than in the moderately steep paddock where 25° slopes covered 55% of the area and grazing pressure was lower. At half maximum stocking rate the fertilizer required to correct transfer losses from slopes over the whole of each paddock from slopes would be approximately 1/3 that required at full stocking rate. This is a reflection largely on the greater amount of

Table 7.2 Simulated P uptake and return in paddocks of differing slope composition at both full and half maximum stocking rates

	Moderately steep paddock			Steep paddock		
	Campsites	25° slope	45° slope	Campsites	25° slopes	45° slopes
<u>Pasture P uptake</u> (kg ha ⁻¹)	49.5	38.2	24.7	49.5	38.2	24.7
<u>Litter P return at:</u>						
Maximum stocking rate	12.4	5.7	5.1	12.4	5.7	5.1
Half maximum stocking rate	12.4	24.3	24.7	12.4	8.5	24.7
<u>Dung P return at:</u>						
Maximum stocking rate	94.7	13.2	4.0	157.5	15.3	4.0
Half maximum stocking rate	52.4	5.6	0	77.5	12.0	0
<u>P transfer at:</u>						
Maximum stocking rate	+ 57.6	- 19.3	- 15.6	+ 120.3	- 17.2	- 15.7
Half maximum stocking rate	+ 15.3	- 8.3	0	+ 40.4	- 17.7	0

dung that was transferred to campsites at the higher stocking rate. It is of interest to note that in the steep paddock the net P loss from 25° slopes at the high stocking rate was less than at the lower level of stocking. This was due to the "spill-over" of dung from campsites to 25° slopes at the higher level of stocking, which compensated more for P losses during grazing. This effect would probably occur in a minority of situations.

7.3.2.2 Effect of overall pasture utilization level on the net P balance on each stratum.

The reduction in pasture utilization level from 75 to 65% on campsites, from 85 to 70% on 25° slopes, and from 70 to 55% on 45° slopes had the effect of lowering stock-carrying capacity from 12.2 to 9.9 stock units ha⁻¹ on the moderately-steep paddock and from 10.2 to 7.3 stock units ha⁻¹ on the steep paddock (Table 7.3). This represented a greater proportional reduction in stock-carrying capacity in the steep paddock because of the relatively greater reduction in grazing efficiency on the 45° slopes, in particular, which constituted the majority of the steep paddock.

The net P balance on 25° slopes and 45° slopes was similar in each paddock, a reflection of the same maximum grazing pressure on similar strata. Some "spill-over" of dung to 25° slopes as a result of the high level accumulation on campsites, still occurred in the steep paddock, as noted in Section 7.3.2.2. This marginally reduced the net P loss on that stratum compared with the transfer loss from areas of similar slope in the moderately-steep paddock. The P surplus in campsites was lower at half-stocking rate than at full-stocking rate, the reduction being similar in proportion to the decrease in stock numbers in each paddock.

Table 7.3 Simulated P uptake and return at maximum pasture grazing utilization levels of 65, 70, and 55% of pasture growth on campsites, 25° slopes, and 45° slopes, respectively, in paddocks of differing average slope.

	Moderately steep paddock			Steep paddock		
	Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
Pasture P uptake (kg ha ⁻¹)	49.5	38.2	24.7	49.5	38.2	24.7
Litter P return (kg ha ⁻¹)	17.3	11.5	11.4	17.3	11.5	11.4
Dung P return (kg ha ⁻¹)	77.1	10.8	2.3	114.6	11.3	2.3
P transfer (kg ha ⁻¹)	+ 44.9	- 15.9	- 11.0	+ 82.4	- 15.4	- 11.0

7.3.2.3 Effect of pasture production and P concentration level on the net P balance on each stratum .

A reduction of 20% in pasture production and associated stock numbers from that in Table 7.2 resulted in a 20% decrease in the P surplus on campsites and in the net P loss from slopes (Table 7.4). Similarly, a decline in pasture P concentration from $4,500\mu\text{g g}^{-1}$ (Table 7.2) to $3,500\mu\text{g g}^{-1}$ resulted in a direct reduction of approximately 22% in the net balance on each strata. Any factors therefore which result in increased pasture production and/or pasture P content will lead directly to increased P losses from slopes by transfer to campsites. Such increased losses will require higher fertilizer inputs to maintain available soil P levels. An increase in pasture growth will support increased animal production, which may partly or completely offset the cost of additional fertilizer required to balance the associated additional transfer losses. Pasture P concentration levels which are higher than required for optimum pasture growth will result, however, in unnecessarily high P transfer losses from slopes and accumulation in campsites. Although advantages have been claimed for enhanced animal health and growth rates resulting directly from high plant P levels (Ozanne et al., 1976), it would appear that the maintenance of such high plant P levels in steep hill country could be relatively costly where increased transfer must be compensated for.

7.4 General Discussion

The data obtained indicate that the level of pasture utilization and thus P intake are the major immediate factors determining the quantity of P transferred from hill slopes. In developed hill country, where

Table 7.4 Simulated P uptake and return at
 (i) pasture production levels equivalent to 80% of those set in Section 7.2.1 and
 (ii) at a pasture P content of $3500\mu\text{g g}^{-1}$, using the same pasture production levels
 set in Section 7.2.1

	Moderately steep paddock			Steep paddock		
	Campsites	25° slopes	45° slopes	Campsites	25° slopes	45° slopes
Pasture production (kg ha^{-1})	8800	6800	4400	8800	6800	4400
P transfer (kg ha^{-1})	+ 46.1	- 15.4	- 12.6	+ 96.2	- 15.4	- 12.6
P transfer at pasture P content of $3500\mu\text{g g}^{-1}$	+ 44.8	- 15.0	- 12.1	+ 93.5	- 15.0	- 12.1

"below-ground" losses of P are at a minimum, the maintenance P fertilizer requirements of pasture on hill slopes will be closely related to the number of animals grazing in those areas. This applies in particular to steep slopes. Because of a natural reluctance of stock to graze steep areas the level of net P transfer from these sites is more sensitive to changes in stocking rate than on easier slopes. The net P surplus in campsites, however, is also very sensitive to changes in stock numbers.

Any increase in animal stocking rate was, because of additional transfer losses shown to cause a relatively greater increase in the P fertilizer required. This was a reflection of the increased transfer of total P to campsites which tend to be always at a higher than adequate level. It is possible where suitably large campsite and ridge crest areas can be omitted from a topdressing programme that some reduction in total fertilizer application may be achieved.

Although total P intake by grazing stock is directly related to stocking rate it is also affected by the P content of the pasture. At any given level of stocking, pasture P concentration will probably be the most important factor determining the level of P transfer loss. This therefore points to the need to avoid luxury rates of fertilizer application. Any factor which tends to minimize luxury P uptake, especially in spring when the greatest proportion of total net P losses occur (Section 3), will predispose toward lower quantities of P transfer. It is possible that the application of rock phosphate with slower release characteristics, or the avoidance of spring topdressing may help in this respect.

The close involvement of the grazing animal with P losses from a pastoral system has been recognised by During (1972) and Karlovsky (1975). During (1972) estimated that on sheep and cattle farms the "above-ground"

net P losses from well-topdressed flat-land pasture would generally not exceed 0.9kg P per stock unit per yr, the losses being approximately 20% higher on dairy farms because of greater removal of P in animal products. Calculations from the field study reported in Section 3 suggest that the average annual P loss from slopes in both paddocks, stocked for high utilization levels and containing pasture of high P content, would be equivalent to approximately 1.3kg P per stock unit.

If it could be assumed that the pasture utilization levels in Table 7.3, the pasture production levels in Table 7.4, and a pasture P concentration of $3,500\mu\text{g g}^{-1}$ are representative of a large proportion of North Island hill country then the combination of these factors should provide an indication of probable P transfer levels in such farmland. Calculations show that net P transfer on the moderately steep paddock would be +27.9, -9.9, and -6.6kg P ha⁻¹ for campsites, 25° slopes, and 45° slopes, respectively, and similarly +51.2, -9.9, and -6.6kg P ha⁻¹ on the relevant strata of the steep paddock. These results suggest that approximately 10kg P must be applied annually to such steep hill pasture merely to compensate for P transfer losses induced by grazing stock. The lower levels of P transfer, both from slopes and to campsites in the above 'more representative' situation than measured in the field trial illustrate the combined effects of lower pasture production, pasture P concentration, and level of pasture utilization.

At the above level of pasture P uptake and stocking rate the total P loss (including an estimated 10% loss in animal products of approximately 0.2kg P per stock unit) would be equivalent to approximately 1.2kg P per stock unit. These estimates suggest that additional P transfer from steep slopes, compared with that occurring on flat-land pasture, is

responsible for at least an additional 0.3kg P per stock unit and that this applies over a range of pasture production and utilization, and P concentration.

The development and use of the "above-ground" model highlighted the need for more information to improve the reliability of some assumptions. It was assumed that animals preferentially grazed strata in the order campsites, 25° slopes, and 45° slopes, achieving maximum utilization of available pasture on one stratum before grazing another. Although this obviously does not strictly apply in practice it is a real tendency and makes the achievement of high levels of overall pasture utilization on steep paddocks more difficult than on those of predominantly easier slopes. A more complete understanding of grazing behaviour in steep pasture would provide a better appreciation of desirable paddock subdivision or management, which would tend to minimise or overcome natural grazing preferences. There is a similar need to evaluate the effects of differing management systems and stocking levels on the camping behaviour of different stock. A greater induced spread of campsites could markedly reduce P losses from moderate slopes. It would be unlikely, however, to affect any greater dung P return to steep slopes although the overall success of any management in modifying camping behaviour may again depend on paddock topographic composition. Many grazing systems have been compared with respect to pasture utilization and animal production benefits. In the hill country situation the evaluation of dung distribution and net P transfer effects related to both camping behaviour and grazing patterns appear to also warrant investigation.

The "above-ground" components of the P cycle appear to offer considerable scope for manipulation to minimize P transfer. It was shown

in Section 3 that, although P losses from slopes by transfer were apparently significant in relation to annual plant P requirements, they were unable to be detected by conventional soil P measurements. Although such losses of P from soil over one year were not measured it is likely that they would, in the absence of additional fertilizer application, have a significant effect over time in reducing the supply of P available for continued plant growth. The extent to which the soil could buffer such P withdrawal, perhaps by P mineralization from organic forms, is not known, nor is the extent to which 'available' soil P must decline before the change could be measureable. In general, routine measurements of P in hill soils would appear to be a relatively insensitive means of evaluating net P transfer. Such measurements made in isolation from other aspects of the P cycle would therefore appear to have only limited value. A more detailed assessment of the role of soil analysis in such investigations seems warranted.

SUMMARY AND CONCLUSIONS

SUMMARY AND CONCLUSIONS

The work presented in this thesis may be summarized as follows:

1. A review of literature relating to the P cycle in grazed pasture revealed that the individual components of the cycle have been studied intensively. Few attempts have been made, however, to assess the relative importance of these components to the P cycle as a whole in any particular situation. Even less attention has been directed towards evaluating the P cycle in grazed pastoral conditions. No studies appear to have been made of the P cycle in grazed hill pastures.
2. The P uptake and return components of the above-ground part of the P cycle in two intensively grazed north- and south-facing, steep hill pastures were shown to be affected largely by ground surface slope. Annual uptake of P by pasture, and more particularly the return to the soil surface of P in dung from grazing sheep, was high on campsites and decreased sharply as slope increased. At a high level of pasture utilization by animals, the P return via litter comprised only approximately 15 to 20% of pasture P uptake. The derived net P balances showed a large net annual gain of P on campsites (50.1 and 119.8kg ha⁻¹) on north and south aspects, respectively) but an appreciable annual net P loss from both 25° slopes (19.5 and 10.0kg ha⁻¹ on north and south aspects, respectively) and 45° slopes (15.3 and 13.8kg ha⁻¹ on north and south aspects, respectively).

The difference between aspects in net P transfer on each stratum could be explained in terms of the effect of differing topographic composition

on animal grazing and camping patterns.

3. It was concluded that under intensive grazing, the net P losses from slopes will be such that maintenance of soil P levels and pasture growth rates will continue to be highly dependent on fertilizer inputs.
4. Marked and largely unexplained fluctuations in the amounts of several soil P parameters, especially in 0-3cm depth soil, together with high estimated, associated errors, were such that neither the effects of fertilizer P addition nor estimated net P loss by transfer could be detected by soil chemical analyses. The possibility of even greater variability in the results obtained for more routine sampling of large hill paddocks for advisory purposes suggests that such analyses may provide only an approximate measure of soil P status in such areas.
5. Using ^{32}P it was found that approximately 85, 92, and 90% of P uptake in spring by mixed pasture on campsites, 25° slopes, and 45° slopes, respectively, was shown to occur from within the surface 7cm of soil. Approximately 90% of P uptake by pasture on all strata was from within 13cm of the P source. It is unlikely that significant P uptake occurred from depths greater than 30cm. The high proportion of P and probably other nutrients, obtained by pasture from near the soil surface on all strata reflects the vulnerable dependence of pasture on adequate levels of moisture in the topsoil. This points to the need for special management, pasture species, or macrofauna which can reduce this vulnerability.
6. Whereas the extent of P uptake by pasture from the upper 3cm of soil was similar both upslope and downslope from a P source, uptake from greater depths was affected by slope. The angle of predominant root activity was found to lie between the vertical and a line normal to

the soil surface, an angle which departed more from the vertical as surface slope increased.

7. Evaluation of the P sorption and desorption characteristics of moderate and high P status soils from the field trial area showed that these could be described by a simple, single 'region' Langmuir model. Although isotopic exchange studies indicated the existence in these soils of at least two regions with differing P sorption characteristics, the sorption and desorption of P could be related largely to region II characteristics as defined by Ryden and Syers (1975a). It would appear that both net sorption and desorption of P occurred predominantly in region II through a dynamic equilibrium with P in region III and that in soil solution.
8. Investigation of the fate in soil of P extracted by water from litter, dung and superphosphate indicated that all sources of P had similar effects on the amounts of water-extractable total P and on Olsen P levels in the soil. A similar availability to plants of the inorganic P from all the three P sources could be expected and this would probably be limited only by the rates of release or mineralization from the original materials. The short-term fate of P added to soil particularly P from dung and litter sources, was more satisfactorily described by measurements of water-extractable P than by Olsen P.
9. The quantity of water-extractable P was found to be higher from air-dried soil than that previously incubated at a high moisture content. (i.e., 90% Field Capacity). A standard preincubation treatment would appear necessary if water-extractable P is to be related to plant-available P.
10. A technique of "double-labelling" soil with both ^{32}P and ^{33}P was

developed as a means of characterizing P taken up by plants over a short period of time. Results showed that plant P uptake occurred from a more labile fraction than that extracted by water (at either a 10:1 or 40:1 water:soil ratio) or by the Olsen reagent. The greater similarity of the isotope ratio in plant-P to that in water-extractable P rather than to Olsen-P demonstrated that water-extractable P was the better index of short-term plant available P.

11. The "double-labelling" or "isotope-ratio" technique showed that ryegrass and white clover did not differ in the form of short-term available P utilized. Greater P uptake by ryegrass than by clover was therefore attributable to more efficient root development and distribution during the P uptake period.
12. In order to extrapolate the results of the field trial to more general situations a mathematical model of the "above-ground" components of the P cycle in grazed, steep hill pastures was developed using data obtained from the north-aspect paddock of the field trial. When validated using field results from the south aspect, the model gave very similar estimates of net P transfer to those measured for all strata.
13. Simulation studies indicated that the quantity of P transfer, both to campsites and away from slopes, was predominantly affected by the total P intake by grazing animals. This was itself affected by the quantity of pasture production and the efficiency of grazing of available pasture on each stratum. The quantity of P transfer from slopes was estimated to increase at a rate greater than that indicated by a simple proportionate increase in stocking rate and to also increase in direct proportion to pasture P content. Both of these factors offer scope for manipulation to influence P losses from the above-ground part of the P cycle.

BIBLIOGRAPHY

BIBLIOGRAPHY

- Acquaye, D.K. 1963. Some significance of soil organic P mineralization in the nutrition of cocoa in Ghana. *Plant and Soil*. 19: 65-80.
- Agricultural Research Council, 1965. The Nutrient Requirements of Farm Livestock No. 2. Ruminants. Agricultural Research Council, London.
- Al-Abbas, A.H., Siriwardene, P.P.G.L., Weerasekara, D.A., and Nagarajah, S. 1967. Isotopic exchange and availability studies of inorganic soil phosphorus fractions on some rice soils of Ceylon. *Isotopes in Plant Nutrition and Physiology*. I.A.E.A.
- Anderson, G. 1960. Factors affecting the estimation of phosphorus esters in soil. *J. Sci. Food and Agric.* 11: 497-503.
- Arambarri, P., and Talibudeen, O. 1959. Factors influencing the isotopically exchangeable phosphate in soils. *Plant and Soil*. 11: 343-354.
- Arnold, G.W. 1960. Selective grazing by sheep of two forage species at different stages of growth. *Aust. J. Agric. Res.* 11: 1026-1033.
- Aslyng, H.C. 1950. The lime and phosphoric acid potentials of soils, their determination and practical application. PHD Thesis. London.
- Aspinall, D. 1961. The control of tillering in the barley plant 1. The pattern of tillering and its relation to nutrient supply. *Aust. J. Biol. Sci.* 14: 493-505.
- Bache, B.W. 1964. Aluminium and iron phosphate studies relating to soils. II. Reactions between phosphate and hydrous oxides. *J. Soil Sci.* 15: 110-116.
- Bache, B.W., and Rogers, N.E. 1970. Soil phosphate supply to plants from some Nigerian soils. *J. Agric. Sci. Camb.* 74: 383-390.

- Bache, B.W., and Williams, E.G. 1971. A phosphate sorption index for soils. *J. Soil Sci.* 22: 289-301.
- Baker, S.B., and Jung, G.A. 1968. Effect of environmental conditions on the growth of four perennial grasses. I. Response to controlled temperature. *Agron. J.* 60: 155-158.
- Balleaux, J.C., and Peaslee, D.E. 1975. Relationships between sorption and desorption of phosphorus by soils. *Soil Sci. Soc. Am. Proc.* 39: 275-278.
- Barber, S.A., Walker, J.M., and Vasey, E.H. 1962. Principles of ion movement through the soil to the plant root. *Trans. Joint Meeting Commissions IV and V Intern. Soc. Soil Sci. New Zealand.* 121-124.
- Barbier, G., Lesaint, M., and Tyszkiewicz, E. 1954. Investigation by means of isotopes of auto diffusion phenomenon in soil and the nutrition of plants. *Ann. Agron.* 6: 923-959.
- Barley, K.P. 1970. The configuration of the root system in relation to nutrient uptake. *Adv. Agron.* 22: 159-201.
- Barley, K.P., and Jennings, A.C. 1959. Earthworms and soil fertility III. The influence of earthworms on the availability of nitrogen. *Aust. J. Agric. Res.* 10: 364-370.
- Barr, C.E., and Ulrich, A. 1963. Phosphorus fractions in high and low phosphorus plants. *J. Agric. Fd. Chem.* 11: 313-316.
- Barrow, N.J. 1961. Mineralisation of nitrogen and sulphur from sheep faeces. *Aust. J. Agric. Res.* 12: 644-650.
- Barrow, N.J. 1975. Chemical form of inorganic phosphate in sheep faeces. *Aust. J. Agric. Res.* 13: 63-67.
- Barrow, N.J. 1977. The adsorption and desorption of phosphate. *Reviews in Rural Science.* III. 'The Efficiency of phosphorus utilization' Ed. G.J., Blair. 83-88.

- Barrow, N.J., and Lambourne, L.J. 1962. Partition of excreted N, S and P between the faeces and urine of sheep being fed pasture. *Aust. J. Soil Res.* 13: 63-67.
- Beetle, A.A. 1952. A relic area in the Wyoming shortgrass plains. *J. Range Mment.* 5: 141-143.
- Ben-Ghedalia, D., Tageri, H., Zamwel, S., and Bondi, A. 1974. Solubility and net exchange of Ca, Mg and P in digesta flowing along the gut of the sheep. *Br. J. Nutr.* 33: 87-94.
- Betson, R.P. 1964. What is watershed runoff? *J. Geophys. Res.* 69: 1491-1552.
- Biederbeck, V.O., and Campbell, C.A. 1973. Soil microbial activity as influenced by temperature trends and fluctuations. *Can. J. Soil Sci.* 53: 363-376.
- Bieleski, R.L. 1973. Phosphate pools, phosphate transport and phosphate availability. *Ann. Rev. Plant Physiol.* 24: 225-252.
- Bingham, F.T. 1949. Soil test for phosphate. *Calif. Agric.* 3: 11-14.
- Birch, H.F. 1961. Phosphorus transformations during plant decomposition. *Plant and Soil.* 15: 347-366.
- Black, J.N. 1955. The interaction of light and temperature in determining the growth of subterranean clover. *Aust. J. Biol. Sci.* 8: 330-343.
- Blair, G.J., Till, A.R., and Smith, R.C.G. 1977. The phosphorus cycle - what are the sensitive areas? *Reviews in Rural Science.* III: 9-19.
- Blaser, R.E., Hammes, R.C., Bryant, H.T., Hardison, W.A., Fontenot, J.P., and Engel, R.W. 1960. The effect of selective grazing on animal output. *Proc. 8th Int. Gland Cong.* 601-606.
- Bole, J.B. 1973. Influence of root hairs in supplying soil phosphorus to wheat. *Can. J. Soil Sci.* 53: 169-175.

- Bouma, D. 1968. The response of subterranean clover (Trifolium subterraneum. L.) to foliar applications of P. Aust. J. Agric. Res. 20: 435-45.
- Bouma, D., and Dowling, E.J. 1966. The physiological assessment of the nutrient status of plants. II. The Effect of the nutrient status of the plant with respect to P, S, K, Ca, or B on the pattern of leaf area changes following the transfer to different nutrient solutions. Aust. J. Agric. Res. 17: 633-646.
- Braithwaite, G.D. 1975. Studies on the absorption and retention of calcium and phosphorus by young and mature calcium deficient sheep. J. Br. Nutr. 34: 311-324.
- Brewster, J.L., Gaucheva, A.N., and Nye, P.H. 1975. The determination of desorption isotherms for soil phosphorus using low volumes of solution and an anion exchange resin. J. Soil Sci. 26: 364-377.
- Bromfield, S.M. 1961. Sheep faeces in relation to the phosphorus cycle under pastures. Aust. J. Agric. Res. 12: 111-123.
- Bromfield, S.M., and Jones, O.L. 1970. The effect of sheep on the recycling of phosphorus in hayed-off pastures. Aust. J. Agric. Res. 21: 699-711.
- Bromfield, S.M., and Jones, O.L. 1972. The initial leaching of hayed-off pasture plants in relation to the recycling of phosphorus. Aust. J. Agric. Res. 23: 811-824.
- Bromfield, S.M., and Simpson, J.R. 1974. Effects of management on soil fertility under pasture. 2. Changes in nutrient availability. Aust. J. Exp. Agric. Anim. Husb. 14: 479-486.
- Brougham, R.W. 1956. The rate of growth of short rotation ryegrass pastures in the late autumn, winter, and early spring. N.Z. J. Sci. Tech. 38A: 78-87.

- Brougham, R.W. 1959. The effects of frequency and intensity of grazing on the productivity of a pasture of short rotation ryegrass and red and white clover. N.Z. J. Agric. Res. 2: 1232-1248.
- Brougham, R.W. 1966. Potential of present type pastures for livestock feeding. N.Z. J. Agric. Sci. 8: 19-22.
- Brougham, R.W. 1970. Frequency and intensity of grazing and their effects on pasture production. Proc. N.Z. Gland Ass. 137-144.
- Brougham, R.W. 1973. Pasture management and production. Proc. Rua. Fmrs. Conf. 169-184.
- Brougham, R.W., Grant, D.A., and Goodall, V.C. 1973. The occurrence of browntop in the Manawatu. Proc. N.Z. Gland Ass. Conf. 86-94.
- Brown, R.H., and Blaser, R.E. 1970. Soil moisture and temperature effects on growth and soluble carbohydrates of Orchardgrass (Dactylis glomerata). Crop Sci. 10: 213-216.
- Bruce, J.G. 1976. Soil map of part of Raglan County, South Auckland, New Zealand. N.Z. Soil Bur. map 100.
- Burnham, C.P., Court, M.N., Jones, R.J.A., and Tinsley, J. 1970. Effect of soil parent material, elevation, aspect and fertilizer treatment on upland grass yields. J. Br. Gland Soc. 25: 272-277.
- Burton, G.W. 1957. Role of tracers in root development investigations. In "Atomic energy and agriculture" Ed. Comer, C.L. American Assoc. Adv. Sci. Washington D.C. Publ. No. 49. 71-80.
- Burwell, R.E., Timmons, D.R., and Holt, R.F. 1975. Nutrient transport in surface runoff as influenced by soil cover and seasonal periods. Soil Sci. Soc. Am. Proc. 39: 523-528.
- Butler, G.W., Greenwood, R.M., and Soper, K. 1959. Effects of shading and defoliation on the turnover of root and nodule tissue of plants of Trifolium repens, T. pratense and Lotus uliginosus. N.Z. J. Agric. Res. 2: 415-426.

- Campbell, A.G. 1966. Pasture under pressure: barriers to higher stocking rates. *Massey Dairy Fmg. Ann.* 90-98.
- Campbell, A.G. 1970. Intensive pasture utilization and animal production in N.Z. *Proc. N.Z. Gland. Ass. Conf.* 145-152.
- Clark, F.E., and Paul, E.A. 1970. The microflora of grassland. *Adv. Agron.* 22: 375-435.
- Cole, C.V., Olsen, S.R., and Scott, C.O. 1953. The nature of phosphate sorption by calcium carbonate. *Soil Sci. Soc. Am. Proc.* 17: 352-356.
- Cole, C.V., Innis, G.S., and Stewart, J.W.B. 1977. Simulation of phosphorus cycling in semi-arid grasslands. *Ecology.* 58: 1-15.
- Cole, C.V., Anderson, R.V., and Campion, M. 1977a. Phosphorus cycling in soil microcosms: Acceleration by bacterial grazers. *Proc. Int. Symp. on Microbial Ecol. Dunedin. N.Z.*
- Colman, R.L. 1971. Factors affecting the response to nitrogen of temperate and tropical grasses. *J. of Aust. Inst. Agric. Sci.* 38: 225-226.
- Cooper, J.P., and Tainton, N.M. 1968. Light and temperature requirements for the growth of tropical and temperate grasses. *Herb. Abst.* 38: 167-176.
- Cowan, W., and Lee, G.F. 1971. Leaves as a source of phosphorus. *Rep. Water Chem. Progs. Univ. of Wisc. Madison. Wisc.*
- Cullen, N.A. 1958. A comparison of phosphatic fertilisers. *N.Z. J. Agric. Res.* 1: 419-431.
- Curry, J.P. 1973. The arthropods associated with the decomposition of some common grass and weed species in the soil. *Soil Biol. Biochem.* 5: 645-657.

- Dalal, R.C., and Hallsworth, E.G. 1977. Measurement of isotopically exchangeable soil phosphorus and interrelationship among parameters of quantity, intensity and capacity factors. *Soil Sci. Soc. Am. Proc.* 41: 81-86.
- Daly, G.T. 1972. The grasslands of New Zealand in "Pastures and pasture plants" Ed. Langer, R.H.M. A.H. and A.W. Reed, Wellington.
- Daughtrey, Z.W., Gilliam, J.W., and Kampreth, E.J. 1973. Soil test parameters for assisting plant-available P of acid organic soils. *Soil Sci.* 115: 438-446.
- Davies, W. 1960. Temperate (and tropical) grasslands. *Proc. 8th. Int. Gland. Cong.* 1-7.
- Davies, E.B., Hogg, D.E., and Hopewell, H.G. 1962. Extent of return of nutrient elements by dairy cattle: possible leaching losses. *Trans. Int. Soc. Soil Sci.* 715-720.
- Dean, L.A. 1954. Yield of phosphorus curves. *Soil Sci. Soc. Am. Proc.* 18: 462-466.
- Donald, C.M. 1956. Competition among pasture plants. *Proc. 7th Int. Gland. Cong.* 80-91.
- Dormaer, J.F. 1972. Seasonal pattern of soil organic phosphorus. *Can. J. Soil Sci.* 52: 107-112.
- Dormaer, J.F., and Webster, G.R. 1964. Losses inherent in ignition procedures for determining total organic phosphorus. *Can. J. Soil Sci.* 44: 1-6.
- Drake, M., and Steckel, J.E. 1955. Solubilisation of soil and rock phosphate as related to root cation exchange capacity. *Soil Sci. Soc. Am. Proc.* 19: 449-450.

- Dunbar, A.D., and Baker, D.E. 1965. Use of isotopic dilution in a study of inorganic phosphorus fractions from different soils. *Soil Sci. Soc. Am. Proc.* 29: 259-262.
- Duncan, D.B. 1955. Multiple range and multiple F tests. *Biometrics* 11: 1-42.
- Dunne, T., and Black, R.D. 1970. Partial area contributions to storm run-off in a small New England watershed. *Water Resources Res.* 6: 1296-1311.
- DuPlessis, S.F., and Burger, R. du T. 1966. The availability of different phosphate fractions. *S. Afr. J. Agric. Sci.* 9: 331-340.
- During, C. 1972. Fertilisers and soils in New Zealand farming. N.Z. Dept. Agric. Bull. 409.
- During, C., Lynch, P.B., McNaught, K.J., and Scott, R.S. 1960. A study of the interaction of P, K, S, Mg, Mo and B fertilisers, and ground limestone, applied to grass-clover pasture. *N.Z. J. Agric. Res.* 3: 950-993.
- During, C., and O'Connor, M.B. 1975. Fertilisers for North Island sheep and cattle farms. *Proc. Rua. Fmrs. Conf.* 30-34.
- Dyer, A. 1974. An introduction to liquid scintillation counting. Heyden and Son. Ltd., London.
- Eadie, J. 1970. Sheep production and pastoral resources. In 'Animal populations in relation to their food resources' Ed. Adam Watson. *Br. Ecol. Sympos.* 10: 7-24.
- Edwards, C.A., and Heath, G.W. 1963. The role of soil animals in breakdown of leaf material. In 'Soil Organisms' (J. Doeksen and J. van der Drift. eds.) North Holland Publ. Co. Amsterdam.

- Egnér, H., Riehm, H., and Domingo, W.R. 1960. Untersuchungen über die chemische bodenanalyse als Grundlage für die Beurteilung des Nährstoffzustandes der Böden. 2. Chemische Extraktionsmethoden zur Phosphor- und Kaliumbestimmung. Kgl. Lantbrukshögsk. Ann. 26: 199-215.
- Eid, M.T., Black, G.A., and Kempthorne, O. 1951. Importance of soil organic and inorganic phosphorus to plant growth at low and high soil temperatures. Soil Sci. 71: 361-370.
- Ekpete, D.M. and Cornfield, A.H. 1966. Effect of varying static and changing moisture levels during incubation and extractability of soil phosphate. Plant and Soil. 24: 317-321.
- Elliott, I.L. 1972. Eutrophication and fertilisers. N.Z. Fert. Mfgers. Ass. Press Forum. 22-29.
- Elliott, I.L. and Lynch, P.B. 1958. Techniques of measuring pasture production in fertiliser trials. N.Z. J. Agric. Res. 1: 498-521.
- Ellis, R.C. 1974. The seasonal pattern of nitrogen and carbon mineralisation in forest and pasture soils in Southern Ontario. Can. J. Soil Sci. 54: 15-28.
- Enwezor, W.O. 1966. The biological transformation of phosphorus during incubation of a soil treated with soluble inorganic phosphorus and with fresh and rotted organic materials. Plant and Soil. 25: 463-466.
- Environmental Protection Agency. 1971. Methods for chemical analysis of water and wastes. U.S. Govt. Print. Office, Wash. D.C. 312 pp.
- Evans, P.S. 1971. Root growth of Lolium perenne. L. II. The effects of defoliation and shading. N.Z. J. Agric. Res. 14: 552-562.

- Evans, P.S. 1972. Root growth of Lolium perenne. L. 3. Investigation of the mechanism of defoliation-induced suppression of elongation. N.Z. J. Agric. Res. 15: 347-355.
- Evans, T.D., and Syers, J.K. 1971. Application of auto-radiography to study the fate of ^{32}P labelled orthophosphate added to soil crumbs. Soil Sci. Soc. Am. Proc. 35: 906-909.
- Finn, J.B., and Mack, A.R. 1964. Differential response of orchardgrass varieties (Dactylis glomerata. L.) to nitrogen and phosphorus, controlled soil temperature and moisture conditions. Soil Sci. Soc. Am. Proc. 28: 782-785.
- Floate, M.J.S. 1970a. Plant nutrient cycling in hill land. Hill Farmg. Res. Orgn. 5th Report 1967-70. 15-34.
- Floate, M.J.S. 1970b. Decomposition of organic materials from hill soils and pastures. 2. Comparative studies on the mineralisation of C, N and P from plant materials and sheep faeces. Soil Biol. Biochem. 2: 173-185.
- Floate, M.J.S. 1970c. Decomposition of organic materials from hill soils and pastures. 3. The effect of temperature on the mineralisation of C, N and P from plant materials and sheep faeces. Soil Biol. Biochem. 2: 187-196.
- Floate, M.J.S. 1970d. Decomposition of organic materials from hill soils and pastures. 4. The effects of moisture content on the mineralisation of C, N and P from plant materials and sheep faeces. Soil Biol. Biochem. 2: 275-283.
- Floate, M.J.S., and Torrance, C.J.W. 1970. Decomposition of organic materials from hill soils and pastures. 1. An incubation method for studying the mineralisation of C, N and P. J. Sci. Fd. Agric. 21: 116-120.

- Frame, J., and Hunt, I.V. 1971. The effects of cutting and grazing systems on herbage production from grass swards. *J. Br. Gland. Soc.* 26: 163-171.
- Freer, M. 1959. Continuous and intermittent grazing experiments reviewed in a wide variety of environments throughout the world. Thesis. Univ. Melbourne.
- Fried, M. 1964. E, L and A values. *Proc. 8th Int. Congr. Soil Sci.* 4: 29-39.
- Fried, M., and Dean, L.A. 1952a. A concept concerning the measurement of available soil nutrients. *Soil Sci.* 73: 263-271.
- Fried, M., and Dean, L.A. 1952b. Phosphate retention by iron and aluminium in cation exchange systems. *Soil Sci. Soc. Am. Proc.* 19: 143-147.
- Fried, M., and Shapiro, R.E. 1956. Phosphate supply patterns of various soils. *Soil Sci. Soc. Am. Proc.* 20: 471-475.
- Gallup, W.D., and Briggs, H.M. 1950. The minimum phosphorus requirements of lambs for phosphorus equilibrium. *J. Anim. Sci.* 9: 426-430.
- Gardner, A.L., and Centeno, G.A. 1966. Removal of the effects of uneven grazing in pasture experiments. *J. Br. Gland. Soc.* 21: 264-269.
- Garwood, E.A. 1967. Seasonal variation in appearance and growth of grass roots. *J. Br. Gland. Soc.* 22: 121-130.
- Garwood, E.A. 1968. Some effects of soil-water conditions and soil temperature on the roots of grasses and clovers. *J. Br. Gland. Soc.* 23: 117-128.
- Gibbs, H.S., Cowie, J.D., and Puller, W.A. 1968. Soils of New Zealand. *N.Z. Soil Bur. Bull.* 26:
- Gibson, A.H. 1967. Physical environment and symbiotic nitrogen fixation. 4. Factors affecting the early stages of nodulation. *Aust. J. Biol. Sci.* 20: 1087-1104.

- Gillingham, A.G. 1973. Influence of physical factors on pasture growth on hill country. Proc. N.Z. Gland. Ass. Conf. 35: 77-85.
- Gillingham, A.G., and Bell, L.D. 1977. Effect of aspect and cloudiness on grass and soil temperatures at a hill site in Raglan County. N.Z. J. Agric. Res. 20: 37-44.
- Gillingham, A.G. and During, C. 1973. Pasture production and transfer of fertility within a long-established hill pasture. N.Z. J. Exp. Ag. 1: 227-232.
- Godwin, D.C., and Wilson, E.J. 1977. Prospects for selecting plants with increased P efficiency. Reviews in Rural Science III.
- Goh, K.M., Gregg, P.E.H., and Brash, D.W. 1977. Isotopic studies on the uptake of sulphur by pasture plants. 1. A method for the direct introduction of ^{35}S isotope into the soil profile under field conditions. N.Z. J. Agric. Res. 20: 221-227.
- Goodall, V.C. 1951. The day and night grazing system. Proc. N.Z. Gland. Ass. Conf. 13: 86-94.
- Grant, S.A. 1970. Temperature and light factors limiting the growth of hill pasture species. Occ. Symp. 4. Br. Gland. Soc. 30-34.
- Gregg, P.E.H., Goh, K.M., and Brash, D.W. 1977. Isotopic studies on the uptake of sulphur by pasture plants 2. Uptake from various soil depths at several field sites. N.Z. J. Agric. Res. 20: 229-233.
- Griffin, R.A., and Jurinak, J.J. 1973. Interaction of phosphate with calcite. Soil Sci. Soc. Am. Proc. 37: 847-850.
- Gunary, D. 1968. The availability of phosphate in sheep dung. J. Agric. Sci. 70: 33-38.
- Gunary, D. 1970. A new adsorption isotherm for phosphate in soil. J. Soil Sci. 21: 72-77.

- Hafez, E.S.E. 1969. The behaviour of domestic animals. Balliere, Tindall and Cassell, London.
- Hagin, J., Hillinger, J., and Olmert, A. 1963. Comparison of several ways of measuring soil phosphorus availability. *J. Agric. Sci.* 60: 245-249.
- Hall, N.S., Chandler, W.F., van Bavel, C.H.M., Reid, P.H., and Anderson, J.H. 1953. A tracer technique to measure growth and activity of plant root systems. *Nth. Carolina Agric. Exp. St. Tech. Bull.* 101.
- Halm, B.J., Stewart, J.W.B., and Halstead, R.L. 1972. The phosphorus cycle in a native grassland ecosystem. Saskatchewan Institute of Pedology Publ. No. R78. CCIBP Report No. 113.
- Hamilton, H.A., and Lessard, J.R. 1960. Phosphorus fractions in a soil sampled at different depths and the effect of lime and fertiliser on oats and clover in a greenhouse test. *Can. J. Soil Sci.* 40: 71-79.
- Hancock, J., and McArthur, A.T.G. 1951. Tips on cow management arising from grazing behaviour studies. *Proc. Rua. Fmrs. Conf.* 32-37.
- Hanley, K.P., and Murphy, M. 1976. Comparative effects of animal manures and fertilisers on grass in pot experiments. *Irish J. Agric. Res.* 15: 146-151.
- Harley, C.P., Moon, H.H., and Regeimbal, L.O. 1951. The release of certain nutrient elements from simulated Orchard Grass mulch. *Proc. Am. Soc. Hort. Sci.* 57: 17-23.
- Harries, J.J., Norrington-Davies, J., and House, K.R. 1974. Competition for phosphate between a diploid and a tetraploid ryegrass. *J. Br. Gland. Soc.* 29: 9-15.

- Harris, W. 1971. The effects of density, cutting height and white clover (Trifolium repens. L.) on the structure of a ryegrass (Lolium spp.) population. J. Agric. Sci. 77: 385-396.
- Harris, W., 1973. Ryegrass genotype-environment interactions in response to density, cutting height and competition with white clover. N.Z. J. Agric. Res. 16: 207-222.
- Harris, W., and Brougham, R.W. 1968. Some factors affecting change in botanical composition in a ryegrass-white clover pasture under continuous grazing. N.Z. J. Agric. Res. 11: 15-38.
- Harris, W., and Thomas, V.J. 1972. Competition among pasture plants. 2. Effects of frequency and height of cutting on competition between Agrostis tenuis and two ryegrass cultivars. N.Z. J. Agric. Res. 15: 19-32.
- Haseman, J.F., Lehr, J.R., and Smith, J.P. 1950. Mineralogical character of some iron and aluminium phosphates containing potassium and ammonium. Soil Sci. Soc. Am. Proc. 15: 76-84.
- Haynes, J.L., and Sayre, J.D. 1956. Response of corn to within row competition. Agron. J. 48: 362-364.
- Haywood, D.G., and Trapnell, B.M.W. 1964. Chemisorption. Butterworths, London. p2.
- Heady, E.O. 1960. Status and methods of research in economic and agronomic aspects of fertiliser response and use. Nat. Acad. Sci. Nat. Res. Comm. Washington, D.C.
- Healy, W.B., 1967. Ingestion of soil by sheep. Proc. N.Z. Soc. An. Prodn. 27: 109-120.
- Harriott, J.B.D., and Wells, D.A. 1963. The grazing animal and sward productivity. J. Agric. Sci. 61: 89-99.

- Hight, G.K. 1976. Problems and potential of farming on North Island hill country. Proc. N.Z. Inst. Agric. Sci. Conf. Palm. Nth.
- Hight, G.K., and Wright, D.B. 1972. The effective utilization of pasture on hill country. Proc. Rua. Fmrs. Conf. 47-61.
- Hilder, E.J. 1966. Distribution of excreta by sheep at pasture. Proc. 10th Int. Gland Congr. 977-981.
- Hilder, E.J., and Mottershead, B.E. 1963. The redistribution of plant nutrients through free grazing sheep. Aust. J. Sci. 26: 88-89.
- Hingston, F.J., Posner, A.M., and Quirk, J.P. 1974. Anion adsorption by goethite and gibbsite. 2. Desorption of anions from hydrous oxide surfaces. J. Soil Sci. 25: 16-26.
- Hoglund, J.H., and Brock, J.L. 1974. Growth of 'Grasslands Huia' and 'Grasslands 4700' white clovers. 1. Effects of temperature and nitrogen. N.Z. J. Agric. Res. 17: 41-45.
- Holliday, R., and Wilman, D. 1962. The effect of white clover, fertiliser nitrogen and simulated animal residues on yield of grassland herbage. J. Br. Gland. Soc. 17: 206-213.
- Holt, R.F., Timmons, D.R., and Latterell, J.J. 1970. Accumulation of phosphates in water. J. Agric. Food Chem. 18: 781-784.
- Hunter, R.F. 1962. Hill sheep and their pasture: A study of sheep grazing in south-east Scotland. J. of Ecol. 50: 651-680.
- Hutton, J.B. 1962. Studies of the nutritive value of New Zealand dairy pastures. 2. Herbage intake and digestibility studies with dry cattle. N. Z. J. Agric. Res. 5: 409-424.
- Hutton, J.B. 1973. Developments in nutrition and managements, and their relation to the future of the New Zealand Dairy industry. Proc. Rua. Fmrs. Conf. 220-232.

- International Atomic Energy Agency, Vienna. 1964. Laboratory training manual on the use of isotopes and radiation in soil-plant relations research. Tech. Rep. Series No. 29. p.11.
- Jackman, R.H., and Mouat, M.C.H. 1972. Competition between grass and clover for phosphate. 2. Effect of root activity, efficiency of response to phosphate and soil moisture. N.Z. J. Agric. Res. 15: 667-675.
- Jackson, M.L. 1958. Soil Chemical analysis. Constable and Co. Ltd. London.
- Jacobs, E., Atsman, D., Kafkafi, U. 1970. A convenient method of placing radioactive substances in soil for studying root development. Agron. J. 62: 303-304.
- Jessop, R.S., Palmer, B., McClelland, V.F., and Jardine, R. 1977. Within season variability of bicarbonate extractable P in wheat soils. Aust. J. Soil Res. 15: 167-170.
- Joblin, A.D.H., O'Connor, M.B., During, C., Gillingham, A.G., and Saunders, W.M.H. 1972. Topdressing hill country. Proc. Rua. Fmrs. Conf. 36-45.
- Johnstone-Wallace, D.B., and Kennedy, K. 1944. Grazing management practices and their relationship to the behaviour and grazing habits of cattle. J. Agric. Sci. 34: 190-197.
- Jones, O.L., and Bromfield, S.M. 1969. Phosphorus changes during the leaching and decomposition of hayed-off pasture plants. Aust. J. Agric. Res. 20: 653-663.
- Jungk, A., and Barber, S.A. 1975. Plant age and the phosphorus uptake characteristics of trimmed and untrimmed corn root systems. Plant and Soil. 42: 227-239.
- Kafkafi, U., Posner, A.M., and Quirk, J.P. 1967. Desorption of phosphate from kaolinite. Soil Sci. Soc. Am. Proc. 31: 348-353.

- Karim, M., Ahmed, F., and Islam, A. 1973. A study of phosphate adsorption by four Bangladesh soils. *Geoderma* 9: 221-227.
- Karlovsy, J. 1961. Phosphate utilisation and phosphate maintenance requirements. *Proc. Rua. Fmrs. Conf.* 142-151.
- Karlovsy, J. 1962. Method of assessing the utilisation of phosphorus on permanent pasture. *Trans. of Joint Meeting of Commissions. IV and V. Int. Soil Sci. Soc.* 1: 726-730.
- Karlovsy, J. 1966. Assessing fertiliser maintenance requirements. *Proc. Rua. Fmrs. Conf.* 115-126.
- Karlovsy, J. 1973. Fertiliser requirements of Mairoa ash soils. *Proc. N.Z. Gland. Ass.* 35: 22-29.
- Karlovsy, J. 1975. Phosphorus utilisation from solid and liquid fertilisers. *N.Z. Fert. Journ.* 45: 3-5.
- Kay, R.N.B. 1960. The rate of flow and composition of various salivary secretions in sheep and calves. *J. Physiol. Lond.* 150: 515-537.
- Khalid, R.A., Patrick, W.H., and DeLanne, R.D. 1977. Phosphorus sorption characteristics of flooded soils. *Soil Sci. Soc. Am. Proc.* 41: 305-310.
- Kissock, W.J. 1966. In hill country sheep trial mobstocking proves superior. *N.Z. Jour. Agric.* 113: 28-33.
- Kydd, D.D. 1957. Grazing intensity - its effect on the sward. *Agric. Review* 2: 25-30.
- Lambert, M.G. 1973. An investigation of some differences between aspects in hill country. *M.Agr.Sc. Thesis. Massey Univ. Lib.*
- Lambourne, L.J. 1956. A comparison between rotational grazing and set stocking for fat lamb production. *N.Z. J. Sci. Tech.* 37A: 555-568.

- Lancashire, J.A., and Keogh, R.G. 1966. Some aspects of the behaviour of grazing sheep. Proc. N.Z. Soc. An. Prod. 26: 22-35.
- Larsen, S. 1950. Studies on the uptake of phosphorus in plants with radiophosphorus as an indicator. K. Veterinaer-og Land bohojskole, Copenhagen, Denmark.
- Larsen, S. 1967. Soil phosphorus. Adv. Agron. 19: 151-210.
- Larsen, S., and Cooke, I.J. 1961. The influence of radioactive phosphate level on the absorption of phosphate by plants and on the determination of labile soil phosphate. Plant and Soil. 14: 43-48.
- Larsen, S., and Gunary, D. 1964. The determination of labile soil phosphate as influenced by the time of application of labelled phosphate. Plant and Soil. 20: 135-142.
- Larsen, S., and Widdowson, A.E. 1970. Evidence of dicalcium phosphate precipitation in a calcareous soil. J. Soil Sci. 21: 364-367.
- Lewis, D.C., and Quirk, J.P. 1967a. Phosphate diffusion in soil and uptake by plants. 1. Self diffusion of phosphate in soils. Plant and Soil. 26: 99-118.
- Lewis, D.C., and Quirk, J.P. 1967b. Phosphate diffusion in soil and uptake by plants. 3. ^{31}P movement and uptake by plants as indicated by ^{32}P auto radiography. Plant and Soil. 26: 445-453.
- Little, D.A. 1972. Studies on cattle with oesophageal fistulae: the relation of the chemical composition of feed to that of the extruded bolus. Aust. J. Exp. Agr. Anim. Husb. 12: 126-130.
- Lofgreen, G.P., Meyer, J.H., and Hull, J.L. 1957. Behaviour patterns of sheep and cattle being fed pasture or soilage. J. Anim. Sci. 16: 773-780.
- Luscombe, P.C. 1976. Evaluation of the potential of a water-extraction of soil phosphate for use in a soil test procedure. B.Ag.Sc.(Hons.) Thesis. Massey Univ. Lib.

- Lynch, P.B. 1947. Methods of measuring the production from grassland. N.Z. J. Sci. Tech. 28A: 385-405.
- Lynch, P.B., and Mountier, N.S. 1954. Cutting techniques in grassland experiments. N.Z. J. Sci. Tech. 36A: 375-385.
- MacDiarmid, B.N., and Watkin, B.R. 1953. 3. Distribution and rate of decay of dung patches and their influence on grazing behaviour. J. Br. Grassl. Soc. 27: 43-54.
- MacKenzie, A.J., and Dean, L.A. 1950. Measurement of ^{32}P in plant materials by use of briquettes. Anal. Chem. 22: 489-490.
- MacLean, A.A. 1965. Extraction of organic P from soils with sodium bicarbonate. Can. J. Soil Sci. 45: 165-170.
- McAuliffe, C.D., Hall, N.S., Dean, L.A., and Hendricks, S.B. 1948. Exchange reactions between phosphates and soils: Hydroxylic surface of soil minerals. Soil Sci. Soc. Am. Proc. 12: 119-123.
- McAuliffe, C.D., Peech, M., and Bradfield, R. 1949. Utilisation by plants of phosphorus in farm manure: 2. Availability to plants of organic and inorganic forms of phosphorus in sheep manure. Soil Sci. 68: 185-195.
- McCall, W.W., Davies, J.F., and Lawton, K. 1956. A study of the effect of mineral phosphates upon the organic phosphorus content of organic soil. Soil Sci. Soc. Am. Proc. 20: 81-83.
- McCarty, P.L. 1967. Sources of nitrogen and phosphorus in water supplies. J. Amer. Water Works Assoc. 59: 344-366.
- McMeekan, C.P. 1959. Principles of animal production. Whitcombe and Tombs. Ltd.
- McMeekan, C.P. 1960. Grazing management. Proc. 8th Int. Grassl. Cong. 21-26.

- McMeekan, C.P., and Walshe, M.J. 1963. The inter-relationships of grazing method and stocking rate in the efficiency of pasture utilisation by dairy cattle. *J. Agric. Sci. Camb.* 61: 147-166.
- McNaught, K.J. 1970. Diagnosis of mineral deficiencies in grass-legume pastures by plant analysis. *Proc. 11th Int. Gland. Congr.* 334-338.
- McNeur, A.J. 1953. Pasture management techniques as applied to strain testing. *Proc. N.Z. Gland. Assoc. Conf.* 157-165.
- Mansell, G.P. 1977. The effect of surface casting earthworms on the plant availability of phosphorus in dead herbage. *Dip. Ag. Sci. Thesis. Massey Univ.*
- Marsh, R., and Campling, R.C. 1970. Fouling of pastures by dung. *Herb. Abstr.* 40: 123-130.
- Marshall, K.C. 1964. Survival of root-nodule bacteria in dry soils exposed to high temperatures. *Aust. J. Agric. Res.* 15: 273-281.
- Martin, J.K., and Molloy, L.F. 1971. A comparison of the organic phosphorus compounds extracted from soil, sheep faeces and plant material collected at a common site. *N.Z. J. Agric. Res.* 14: 329-333.
- Martin, J.K., and Wicken, A.J. 1966. Soil organic phosphorus. 4. Fractionation of organic P in alkaline soil extracts and the identification of inositol phosphates. *N.Z. J. Agric. Res.* 13: 529-535.
- Martin, W.E., and Mikkelson, D.S. 1960. Grain fertilisation in California. *Calif. Agric. Exp. Sta. Bull.* 775.
- Mattingly, G.E.G., and Talibudeen, O. 1960. Isotopic exchange of phosphates in soil. *Rep. Rothamst. Exp. Sta.* 248-265.
- Maurya, P.R., Ghildyal, B.P., and Sharma, D. 1973. Note on the determination of specific activity of ^{32}P for the study of root distribution in soil-root cores. *Indian J. Agric. Sci.* 43: 886-887.

- May, P.F., Till, A.R., and Cumming, M.J. 1972. Systems analysis of ^{35}S kinetics in pastures grazed by sheep. *J. App. Ecol.* 9: 25-49.
- May, P.F., Till, A.R., and Downes, A.M. 1968. Nutrient cycling in grazed pastures. 1. A preliminary investigation of the use of ^{35}S gypsum. *Aust. J. Agric. Res.* 19: 531-543.
- Maynard, L.A. 1947. *Animal nutrition*. McGraw-Hill Book Co. Inc. N.York.
- Mehta, N.C., Legg, J.O., Goring, C.A.I., and Black, C.A. 1954. Determination of organic phosphorus in soils. 1. Extraction method. *Soil Sci. Soc. Am. Proc.* 18: 443-449.
- Mekhael, D., Amer, F., and Kadry, L. 1965. Comparison of isotopic dilution methods for estimation of plant available soil phosphorus. *Proc. Symp. Isotopes and radiation in 'Soil-plant nutrition studies'* I.A.E.A. Vienna. 437-438.
- Melville, J., and Sears, P.D. 1953. Pasture growth and soil fertility. 2. The influence of red and white clovers, superphosphate, lime and dung and urine on the chemical composition of pasture. *N.Z. J. Sci. Tech.* 35A: 30-41.
- Metson, A.J., and Hurst, F.B. 1953. Effects of sheep dung and urine on a soil under pasture at Lincoln, Canterbury, with particular reference to potassium and nitrogen equilibria. *N.Z. J. Sci. Tech.* 35A: 327-359.
- Meyer, J.H., Lofgreen, G.P., and Hull, J.L. 1957. Selective grazing by sheep and cattle. *J. Anim. Sci.* 16: 766-772.
- Middleton, K.R., and Toxopeus, M.R.J. 1973. Nutrient solutions for glasshouse trials. *Plant and Soil.* 38: 219-226.
- Minson, D.J., Raymond, W.F., and Harris, C.E. 1960. Studies on the digestibility of herbage. 8. The digestibility of S37 Cocksfoot, S23 Ryegrass and S24 Ryegrass. *J. Br. Grass. Soc.* 15: 174-180.

- Mitchell, K.J. 1956a. Growth of pasture species under controlled environment. 1. Growth at various levels of constant temperature. N.Z. J. Sci. Tech. 38A: 203-216.
- Mitchell, K.J. 1956b. The influence of light and temperature on the growth of pasture species. Proc. 7th Int. Grass Cong. 58-69.
- Mitchell, K.J., and Coles, S.T.J. 1955. Effects of defoliation and shading on short rotation ryegrass. N.Z. J. Sci. Tech. 36A: 586-604.
- Mitchell, K.J., and Lucanus, R. 1962. Growth of pasture species under controlled environment. 3. Growth at various levels of constant temperature with 8 and 16 hours of uniform light per day. N.Z. J. Agric. Res. 5: 135-144.
- Moore, W.J. 1966. Physical Chemistry. Longmans Green and Co. Ltd. London. W.1.
- Mortimer, C.H. 1941. The exchange of dissolved substances between mud and water in lakes. J. Ecol. 29: 280-329.
- Mortimer, C.H. 1942. The exchange of dissolved substances between mud and water in lakes. J. Ecol. 30: 147-201.
- Mouat, M.C.H., and Walker, T.W. 1959. Competition for nutrients between grasses and white clover. 1. Effect of grass species and nitrogen supply. Plant and Soil. 11: 30-40.
- Muljadi, D., Posner, A.M., and Quirk, J.P. 1966. The mechanism of phosphate adsorption by kaolinite, gibbsite and pseudo boehmite. J. Soil Sci. 17: 212-247.
- Murphy, J. and Riley, J.P. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27: 31-36.
- Nagarajah, S., Posner, A.M., and Quirk, J.P. 1968. Desorption of phosphate from kaolinite by citrate and bicarbonate. Soil Sci. Soc. Am. Proc. 32: 507-510.

- Nelson, W.L., Meylich, A., and Winters, E. 1953. In 'Soil and Fertiliser Phosphorus' Pierre, W.H. and Normans, A.G. Eds. Agron. 4. Academic N.Y.
- Newbould, P., 1969. The absorption of nutrients by plants from different zones in soil. In "Ecological Aspects of the Mineral Nutrition of Plants" pp. 177-190. Ed. I.H. Rorison. Blackwell Scientific Publns. London.
- Newbould, P., and Taylor, R., 1964. Uptake of nutrients from different depths in soil by plants. Proc. 8th Int. Congr. of Soil Sci. IV. 731-742.
- Newbould, P., Taylor, R., and Howse, K.R. 1971. The absorption of phosphate and calcium from different depths in soils by swards of perennial ryegrass. J. Br. Grass. Soc. 26: 201-208.
- Newman, E.I., and Andrews, R.E. 1973. Uptake of phosphorus and potassium in relation to root growth and root density. Plant and Soil. 38: 49-69.
- Norman, M.J.T. and Green, J.O. 1958. The local influence of cattle dung and urine upon the yield and botanical composition of permanent pasture. J. Br. Grass. Soc. 13: 39-45.
- Nye, P.H. and Foster, W.N.M. 1956. Do plants vary in their ability to utilise less readily available soil phosphate? Trans. 11th Int. Cong. Soil Sci. D. 257-262.
- Nye, P.H. and Foster, W.N.M. 1958. A study on the mechanism of soil phosphate uptake in relation to plant species. Plant and Soil 9: 338-352.
- Nye, P.H. and Foster, W.N.M. 1960. The use of radio-isotopes to study plant feeding zones in natural soil. Trans. 7th Int. Congr. Soil Sci. 215-221.

- O'Brien, T.A., Moorby, J., and Whittington, W.J. 1967. The effect of management and competition on the uptake of ³²phosphorus by ryegrass, meadow fescue and their natural hybrid. *J. appl. Ecol.* 4: 513-520.
- Olsen, S.R., Cole, C.V., Watanabe, F.S., and Dean, L.A. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *Circ. U.S. Dept. Agric.* 939.
- Olsen, S.R., and Watanabe, F.S. 1963. Diffusion of phosphorus as related to soil texture and plant uptake. *Soil Sci. Soc. Am. Proc.* 27: 648-653.
- Omanwar, P.K., and Robertson, J.A. 1970. Movement of phosphorus to barley roots growing in soil. *Can. J. Soil Sci.* 50: 57-64.
- Ozanne, P.G., Asher, C.J., and Kirton, D.J. 1964. Root distribution in a deep sand and its relationship to the uptake of added potassium by pasture plants. *Aust. J. Agric. Res.* 16: 785-800.
- Ozanne, P.G., Purser, D.B., Howes, K.M.W., and Southey, I. 1976. Influence of phosphorus content on feed intake and weight gain in sheep. *Aust. J. Exp. Agr. Anim. Husb.* 16: 353-360.
- Patel, A.S., and Cooper, J.P. 1961. The influence of seasonal changes in light energy on leaf and tiller development in ryegrass, timothy and meadow fescue. *J. Br. Grassl. Soc.* 16: 299-308.
- Peacock, J.M. 1970. Interaction between the sward and the environment in the field. *Hurley Grassl. Res. Inst. Ann. Rep.*
- Peaslee, D.E., and Balleaux, J.C. 1977. Short term replenishment of soil solution phosphorus. *Soil Sci. Soc. Am. Proc.* 41: 529-531.
- Patterson, M.S. and Green, R.C. 1965. Measurement of low energy beta emitters in aqueous solution by liquid scintillation counting of emulsions. *Anal. Chem.* 37: 854-857.

- Peterson, R.G., Woodhouse, W.W., and Lucas, H.L. 1956a. The distribution of excreta by freely grazing cattle and its effect on pasture fertility. 1. Excretal distribution. *Agron. J.* 48: 440-444.
- Peterson, R.G., Woodhouse, W.W., and Lucas, H.L. 1956b. The distribution of excreta by freely grazing cattle and its effect on pasture fertility. 2. Effect of returned excreta on the residual concentration of some fertiliser elements. *Agron. J.* 48: 444-449.
- Petrie, A.H.K. 1937. Physiological entogeny in plants and its relation to nutrition. 3. The effect of nitrogen supply on the drifting composition of the leaves. *Aust. J. Exp. Biol. Med. Sci.* 15: 385-404.
- Pirson, A., 1955. Functional aspects in mineral nutrition of green plants. *Ann. Rev. Pl. Phys.* 6: 71-114.
- Preston, R.L., and Pfander, W.H. 1964. Phosphorus metabolism in lambs fed varying phosphorus intakes. *J. Nutr.* 83: 369-378.
- Probert, M.E. 1972. The dependence of isotopically exchangeable phosphate (L-value) on phosphate uptake. *Plant and Soil.* 36: 141-148.
- Radcliffe, J.E., Dale, W.R., and Viggers, E. 1968. Pasture production measurements on hill country. *N.Z. J. Agric. Res.* 11: 685-700.
- Radcliffe, J.E., Young, S.R., and Clarke, D.G. 1976. Effects of sunny and shady aspects on pasture yield, digestibility and sheep performance in Canterbury. *Proc. N.Z. Gland. Assoc.* 38: 66-77.
- Ragan, R.M. 1967. An experimental investigation of partial area contributions. *Int. Assoc. Sci. Hydrol. Proc. Berne. Symp.*
- Rennes, A. 1978. Some aspects of the movement and fate of applied phosphate in soils and run-off water. PHD Thesis. Massey Univ.
- Rennie, D.A., and McKercher, R.B. 1959. Adsorption of phosphate by four Saskatchewan soils. *Can. J. Soil Sci.* 39: 64-75.

- Rhoades, E.P., Locke, L.F., Taylor, H.M. and McIlvain, E.H. 1964. Water intake on a sandy range as affected by 20 years of differential cattle stocking rates. *J. Range Mment.* 17: 185-190.
- Rumball, P.J., and Esler, A.E. 1968. Pasture patterns on grazed slopes. *N.Z. J. Agric. Res.* 11: 575-588.
- Russell, E.W. 1954. Soil conditions and plant growth. Longmans, Green and Co. Ltd. London.
- Russell, G.C. and Low, P.F. 1954. Reaction of phosphate with kaolinite in dilute solution. *Soil Sci. Soc. Am. Proc.* 18: 22-25.
- Ryden, J.C. 1975. The reactions and mechanisms of inorganic phosphate sorption by soils. PHD Thesis. Massey University. N.Z. 171 pp.
- Ryden, J.C., and Syers, J.K. 1975a. Charge relationships of phosphate sorption. *Nature* 255: 51-53.
- Ryden, J.C., and Syers, J.K. 1975b. Relationship of ionic strength and cation effects on phosphate sorption by soils. *J. Soil Sci.* 26: 395-406.
- Ryden, J.C., and Syers, J.K. 1977. Origin of the labile phosphorus pool in soils. *Soil Sci.* 123: 353-361.
- Ryden, J.C., Syers, J.K., and Harris, R.F. 1972. Potential of an eroding urban soil for the phosphorus enrichment of streams. 1. Evalaution of methods. *J. of Env. Qual.* 1: 430-434.
- Ryden, J.C., McLaughlin, J.R., and Syers, J.K. 1977a. Mechanism of phosphate sorption by soils and hydrous ferric oxide gel. *J. Soil Sci.* 28: 72-92.
- Ryden, J.C., McLaughlin, J.R., and Syers, J.K. 1977b. Effects of ionic strength on chemisorption and potential determining sorption of phosphate by soils. *J. Soil Sci.* 28: 62-71.

- Saunders, W.M.H. 1958. The effect of different phosphate fertilisers on soil pH and the consequent effect on phosphate retention. N.Z. J. Agric. Res. 1: 675-682.
- Saunders, W.M.H. 1965. Phosphate retention by New Zealand soils and its relationship to free sesquioxides, organic matter and other soil properties. N.Z. J. Agric. Res. 8: 30-57.
- Saunders, W.M.H., and Auld, M.W. 1969. Topdressing within a hill country farm. Proc. Rua. Fmrs. Conf. 16-25.
- Saunders, W.M.H., and Williams, E.G. 1955. Observations on the determination of total organic phosphorus in soils. J. Soil Sci. 6: 254-267.
- Schouten, C.J.J.H. 1976. Origin and output of suspended and dissolved material from a catchment in Northland, (N.Z.) with particular reference to man induced changes. Publication series of the Physics and Geophysics Laboratory, Univ. of Amersterdam, No. 23. 180 pp.
- Sears, P.D. 1944. Pasture plot measurement technique. N.Z. J. Sci. Tech. 25: 177-190.
- Sears, P.D. 1950. Soil fertility and pasture growth. J. Br. Gland Soc. 5: 267-280.
- Sears, P.D. 1956. The effect of the grazing animal on pasture. Proc. 7th Int. Gland. Congr. 92-101.
- Sears, P.D., Goodall, V.C., and Newbold, R.P. 1948. The effect of sheep droppings on yield botanical composition and chemical composition of pasture. 2. Results for the years 1942-1944 and final summary of the trial. N.Z. J. Sci. Tech. A30. 231-250.
- Sears, P.D., and Newbold, R.P. 1942. The effect of sheep droppings on yield, botanical composition and chemical composition of pasture. N.Z. J. Sci. Tech. A24. 36-61.

- Sears, P.D., and Thurston, W.A. 1953. Effects of sheep droppings on yield, botanical composition, and chemical composition of pasture. 3. Results of field trials at Lincoln, Canterbury, for the years 1944-1947. N.Z. J. Sci. Tech. A34. 445-459.
- Shapiro, R.E., and Fried, M. 1959. Relative release and retentiveness of soil phosphates. Soil Sci. Soc. Am. Proc. 23: 195-205.
- Sharpley, A.N., 1977. Sources and transport of phosphorus and nitrogen in a stream draining a dominantly pasture catchment. PHD Thesis. Massey Univ. N.Z. 291 pp.
- Sharpley, A.N., and Syers, J.K. 1976. Seasonal variation in casting activity and in the amounts and release to solution of phosphorus forms in earthworm casts. Soil Biol. Biochem. 9: 227-231.
- Shaw, K. 1958. Studies of nitrogen and carbon transformations in soil. PHD Thesis. London.
- Sheard, R.W. 1974. Nitrogen enhancement of surface applied fertilizer phosphorus uptake by forage species. Can. J. Soil Sci. 54: 89-104.
- Simpson, J.R., Bromfield, S.M., and McKinney, G.T. 1974. Effects of management on soil fertility under pasture. 1. Influence of experimental grazing and fertiliser systems on growth, composition and nutrient status of the pasture. Aust. J. Exp. Agric. Anim. Husb. 14: 470-478.
- Singh, B.B., and Jones, J.P. 1977. Phosphorus sorption isotherm for evaluating phosphorus requirements of lettuce at five temperature regimes. Plant and Soil. 46; 31-44.
- Sissingh, H.A. 1969. The dissolution of soil phosphoric acid by water extraction in relation to the development of a new P-water method. Forsch. 23: 110-120.

- Small, J.G.C., and Joffe, A. 1968. Physiological studies on the genus Trifolium with special reference to the South African species.
2. Influence of root temperature on growth, nodulation and symbiotic nitrogen fixation. 8th Afric. J. Agric. Sci. 11: 41-56.
- Smetham, M. 1973. In 'Pastures and pasture plants' Ed. Langer, R.H.M.
- Smith, A.N. 1966. The role of inorganic soil phosphates in supplying phosphorus to the wheat plant. Agrochemica. 11: 79-91.
- Smith, S.J., and Legg, J.O. 1971. Reflections on the A value concept of soil nutrient availability. Soil Sci. 112: 373-375.
- Smith, M.E., and Dawson, A.D. 1976. Hill country grazing management. Proc. N.Z. Gland. Assoc. 38: 47-65.
- Sørensen, L.H. 1974. Rate of decomposition of organic matter in soil as influenced by repeated air drying-rewetting and repeated additions of organic material. Soil Biol. Biochem. 6: 287-292.
- Sprague, V.G. 1943. The effects of temperature and day length on seedling emergence and early growth of several pasture species. Soil Sci. Soc. Am. Proc. 8: 287-294.
- Suckling, F.E.T. 1954. Pasture management trials on unploughable hill country at Te Awa. i. Establishment of experimental area and results 1949-51. N.Z. J. Sci. Tech. A36: 237-273.
- Suckling, F.E.T. 1959. Pasture management trials, on unploughable hill country at Te Awa. 2. Results for 1951-57. N.Z. J. Agric. Res. 2: 488-542.
- Suckling, F.E.T. 1975. Pasture management trials on unploughable hill country at Te Awa. N.Z. J. Exp. Agr. 3: 351-436.
- Syers, J.K. 1974. Effect of phosphatic fertilisers on agriculture and the environment. N.Z. Agric. Sci. 8: 149-164.

- Syers, J.K., Williams, J.D.H., and Walker, T.W. 1968. The determination of total phosphorus in soils and parent materials. *N.Z. J. Agric. Res.* 11: 757-762.
- Syers, J.K., Shah, R., and Walker, T.W. 1969. Fractionation of P in two alluvial soils and particle size separates. *Soil Sci.* 108: 283-289.
- Syers, J.K., Evans, T.D., Williams, J.D.H., and Murdock, J.T. 1971. Phosphate sorption parameters of representative soils from Rio-Grande do Sul, Brazil. *Soil Sci.* 112: 267-275.
- Syers, J.K., Browman, G.M., Smillie, G.W., and Corey, R.B. 1973. Phosphate sorption by soils evaluated by the Langmuir adsorption equation. *Soil Sci. Soc. Am. Proc.* 37: 358-363.
- Syers, J.K., and Williams, J.D.H. 1977. Amounts and forms of phosphorus and arsenic in soils. Chapter In 'Soil Chemistry' Eds. J.M. Bremner and G. Chesters. Marcel Dekker. In press.
- Talibudeen, O. 1957. Isotopically exchangeable phosphorus in soils. 2. Factors influencing the estimation of labile phosphorus. *J. Soil Sci.* 8: 86-96.
- Talibudeen, O. 1974. The nutrient potential of soil. *Soils Ferts.* 37: 41-45.
- Taylor, A.W., Edwards, W.M., and Simpson, E.C. 1971. Nutrients in streams draining woodland and farmland near Coshocton, Ohio. *Water Resources Res.* 7: 81-90.
- Taylor, A.W., and Gurney, E.L. 1962. Phosphate equilibria in an acid soil. *J. Soil Sci.* 13: 187-197.
- Terman, G.L., and Khasawneh, F.E. 1968. Crop uptake of fertiliser and soil phosphorus in relation to calculated A values. *Soil Sci.* 105: 346-354.

- Thomas, G.W., and Peaslee, D.E. 1975. In 'Soil testing and plant analysis' Walsh L.M., and Beeton, J.D. Eds. Soil Sci. Soc. Am. Wisconsin. U.S.A.
- Thompson, L.M., and Black, C.A. 1949. The mineralisation of organic phosphorus nitrogen and carbon in Clarion and Webster soils. Soil Sci. Soc. Am. Proc. 14: 147-151.
- Troughton, A. 1957. The underground organs of herbage grasses. Bull. of Comm. Agr. Bur. of Pastures and Crops. 44: 163pp.
- Troughton, A. 1960. Growth correlations between roots and shoots of grass plants. Proc. 8th Int. Gland. Congr. 280-283.
- Truog, E. 1930. The determination of readily available phosphorus of soils. J. Am. Soc. Agron. 22: 874-882.
- Uyo, L.J. 1974. Plant uptake of ^{32}P from different depths of a yellow-grey earth soil. B.Ag.Sc. (Hons) Thesis. Massey Univ.
- Valentine, I., and Barley, K.P. 1976. Effects of soil temperature and phosphorus supply on an annual grass and clover grown in monoculture and in mixed culture. Plant and Soil 44: 163-177.
- Vallis, I., Henzell, E.F., Martin, A.E., and Ross, P.J. 1973. Isotopic studies on the intake of nitrogen by pasture plants. V. ^{15}N -balance experiments in field micro-plots. Aust. J. Agric. Res. 24: 693-702.
- Van der Elst, F., and Karlovsky, J. 1953. Phosphate fertilisers. N.Z. J. Agric. 86: 146.
- Van der Paauw, F. 1971. An effective water extraction method for the determination of plant-available phosphorus. Plant and Soil 34: 467-481.
- Vartha, E.W. 1973. Effects of shade on the growth of Poa trivialis and perennial ryegrass. N.Z. J. Agric. Res. 16: 38-42.

- Walker, T.W. 1965. In 'Experimental Pedology' Eds. Hallsworth, E.G., and Crawford D.V. Butterworths, London. 295-315.
- Walker, T.W., and Adams, A.F.R. 1958. Studies on soil organic matter. 1. Influence of P content of parent materials on accumulations of C; N and S and organic P in grassland soils. *Soil Sci.* 85: 307-318.
- Walker, T.W., Adams, A.F.R., and Orchiston, H.D. 1955. The effects and interactions of sulphur, phosphorus, and molybdenum on the growth and composition of grasses. *N.Z. J. Sci. Tech.* A36: 470-482.
- Walker, T.W., and Syers, J.K. 1974. The fate of phosphorus during pedogenesis. *Geoderma* 15: 1-19.
- Wallace, L.R. 1956. The intake and utilisation of pasture by grazing dairy cattle. *Proc. 7th Int. Gland. Cong.* 134-145.
- Watkin, B.R. 1954. The animal factor and levels of nitrogen. *J. Br. Gland. Soc.* 9: 35-46.
- Watkin, B.R. 1957. The effect of dung and urine and its interactions with applied nitrogen, phosphorus and potassium on the chemical composition of pasture. *J. Br. Gland Soc.* 12: 264-277.
- Weaver, J.E. 1926. Root development of field crops. McGraw-Hill, New York.
- Weeda, W.C. 1967. The effect of cattle dung patches on pasture growth, botanical composition and pasture utilisation. *N. Z. J. Agric. Res.* 10: 150-159.
- Weir, W.C., and Torrell, D.T. 1959. Selective grazing by sheep as shown by a comparison of the chemical composition of range and pasture forage obtained by hand clipping and that collected by esophageal fistulated sheep. *J. Anim. Sci.* 18: 641-649.
- Wheeler, J.L. 1958. The effect of sheep excreta and nitrogenous fertiliser on the botanical composition and production of hay. *J. Br. Gland Soc.* 13: 196-202.

- White, R.E. 1973. Studies on mineral ion absorption by plants. 2. The interaction between metabolic activity and the rate of P uptake. *Plant and Soil*. 38: 509-523.
- White, R.E., and Taylor, A.W. 1977. Reactions of soluble phosphate with acid soils: The interpretations of adsorption - desorption isotherms. *J. Soil Sci.* 28: 314-328.
- White, R.P., and Ellis, B.G. 1968. Routine counting of ^{32}P in coloured solutions from dry ashed plant samples utilising Cerenkov radiation. *Soil Sci. Soc. Am. Proc.* 32: 740-741.
- Wilkins, J. 1967. The effects of high temperatures on certain root nodule bacteria. *Aust. J. Agric. Res.* 299-304.
- Will, G.M. 1968. Some aspects of organic matter formation and decomposition in pumice soils growing *Pinus radiata* forest. *Trans. 9th Int. Conf. Soil Sci.* 3: 237-246.
- Williams, J.D.H., Syers, J.K., Walker, T.W., and Rex, R.W. 1970. A comparison of methods for the determination of soil organic phosphorus. *Soil Sci.* 110: 13-18.
- Williams, R.F., 1948. The effects of phosphorus supply on the rates of intake of phosphorus and nitrogen and upon certain aspects of phosphorus metabolism in Gramineous plants. *Aust. J. Sci. Res.* B 1. 333-361.
- Williams, R.F. 1955. Redistribution of mineral elements during development. *Ann. Rev. Pl. Phys.* 6: 25-42.
- Williams, E.G., Scott, N.M., and McDonald, M.J. 1958. Soil properties and phosphate sorption. *J. Sci. Fd. Agr.* 9: 551-559.
- Wilson, A.T. 1968. The chemistry underlying the phosphate problem in agriculture. *Aust. J. Sci.* 31: 55-61.

- Wolten, K.M. 1955. The effect of sheep excreta and fertiliser treatments on the nutrient status of a pasture soil. *J. Br. Grassland Soc.* 10: 240-253.
- Wolten, K.M. 1963. An investigation into the simulation of nutrient returns by the grazing animal in grassland experimentation. *J. Br. Grassland Soc.* 18: 213-219.
- Wolten, K.M., Brockman, J.S., and Shaw, P.G. 1970. The simulation of animal returns in grassland experimentation. *J. Br. Grassland Soc.* 25: 255-260.
- Wright, E. 1955. Site of phosphorus absorption in the sheep. *Nature.* 176: 351-352.
- Yoeman, P.G. 1973. Potential of hill country farming in the King Country. *Proc. N.Z. Grassland Assoc.* 35: 44-51.

APPENDICES

Appendix I

Pastoral land in New Zealand occupies about 13 million hectares (ha) which represent 95% of the farmed area. About 1/3 of this is in tussock grassland or high country, mainly in the South Island; a further 1/3 (4.5 million ha) is made up of hill country, predominantly in the North Island.

Hill country topography varies from rolling to steep although most farms have at least some small area of relatively flat land. Rainfall ranges from a relatively low annual level (750 mm) with summer drought conditions in some parts of Hawkes Bay, Wairarapa, and Wanganui, to a rainfall of more than 2000 mm in the western North Island, Northland, and higher altitude areas. Regional temperature and wind levels tend to be modified by land forms to produce contrasting microclimates. Aspect differences may be marked and reflected in differing pasture growth patterns and species composition. Pasture growth continues year round in most areas.

The original "bush burn" seed mixtures (Daly, 1972) sown following early development have generally reverted to predominantly browntop (Agrostis tenuis) pastures of very low legume content and nitrogen status. As recently as 1967-68 Brougham et al. (1973) recorded more than an 80% frequency of occurrence of browntop in Manawatu hill pastures.

North Island hill soils range from Yellow-grey earths (Gibbs et al., 1968) in parts of Hawkes Bay and Wairarapa to Northern yellow-brown earths in Northland. The central North Island was originally covered by various ash showers. Rhyolitic ash blanketed the central and eastern North Island producing "bush sick" or cobalt-deficient pumice soils while mainly andesitic ash formed Yellow-brown loams in the remainder of the ash covered

area. Ash was lost from steep slopes and so steepland soils therefore are derived almost entirely from the underlying mudstone, siltstone, and sandstone parent materials (Steepland yellow-grey earths and Central yellow-brown earths). Some of these soils have severe erosion problems. The erosion of ash from steep slopes, but not from many associated ridge crests or rolling and flat sites, has produced a very complicated soil pattern. Consequently, soils in many areas are more correctly mapped as complexes than as uniform soil types.

Hill country provides most of the ewes and weaner cattle used in the production of export lamb, mutton, and beef from predominantly lowland farms. Total hill country stock numbers are about 31 million. These are stocked at rates ranging from 4 stock units/ha on drier hill country to about 10 stock units/ha on wetter areas (Brougham, 1973). Sheep breeds vary widely (Perendale, Cheviot, Corriedale, Coopworth, and Border Leicester) although Romney and Romney crosses predominate. Aberdeen Angus is the predominant beef breed although Herefords and Friesians and various crosses of these breeds are used.

Present fertilizer topdressing recommendations for hill and steepland soils are based largely on trials conducted on adjacent flat or terrace sites with similar parent materials and on some observational fertilizer responses. Very few trials, which also provide measures of pasture dry matter responses to topdressing, have been located on hill or steep slopes. This is particularly the case in relation to maintenance topdressing needs. During (1972), in particular, but also Karlovsky (1973), and During and O'Connor (1975) have made recommendations on phosphate requirements. The limited trials relating to other nutrients suggest that K responses may be obtained on ash soils and that Mo, S, and lime deficiencies can limit growth on steepland soils from sedimentary parent materials.

Variable topography and associated pasture species composition, large paddock sizes, and predominantly set-stocking grazing policies are all seen as important factors limiting better utilization of available pasture. Consequently, such factors retard further increases in animal production from this class of country. Estimates of possible increases seen to be obtainable by utilising existing technology have been quoted as 70% (Yoeman, 1973), 300% (Brougham, 1973), and 200% (Hight, 1976). While greater total production could be achieved by better utilization of existing pasture this may also lead to increased levels of nutrient transfer. A better understanding of the relationship between grazing management and fertilizer requirements would therefore appear even more necessary than on flat land as stock numbers on hill country increase.

Appendix II

TOPOGRAPHIC SURVEY

A topographic survey provided a measure of the relationship between surface slope and area within each paddock and was conducted as follows:

Surface slope (i.e., as the departure from horizontal) was measured along major ridges within each paddock. At approximately equidistant intervals along each ridge, and at the head of each gully, transects were located vertically downslope from ridge crest to gully floor. On all transects slope was recorded at 2-m intervals to the nearest 5° . A total of 643 records were taken in the north aspect paddock and 582 in the south paddock.

Detailed results are shown in Fig. A and summarized in Table 3.1. These show the overall greater steepness of the south aspect paddock which contained a smaller proportion of campsites and a greater proportion of tracks, indicative of the greater area of steep slopes (i.e., $35^{\circ}+$) than the north facing paddock. The proportion of the total area in camps plus tracks was 31.3% and 31.8% in the north and south aspect paddocks, respectively. Not all tracks could be regarded as equivalent to campsites, particularly on the south aspect where they were overall transversely more steep. This may be indicative of a relatively immature stage of track development compared with those on the north aspect.

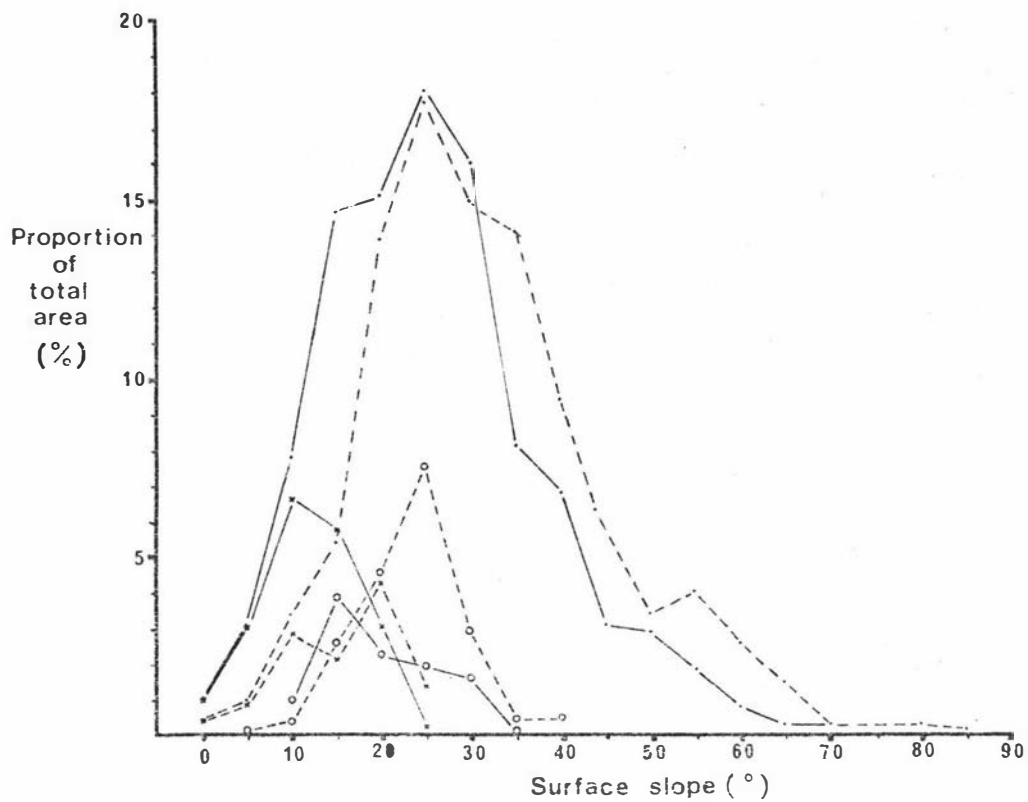


FIGURE A. Slope:area distribution curves for the total area, for campsites and for tracks in paddocks of both north- and south-facing aspect. Solid lines = north aspect and broken lines = south aspect. · = total area, x = campsites, and o = tracks.

Appendix III Estimated total grazing days per season, mean annual stocking rate and stock weight changes and mean weight changes per stock unit on north and south aspect paddocks

<u>Season</u>	Total grazing days (G.D.)	Total stock numbers x grazing days*		Mean weight change (kg SU ⁻¹ GD ⁻¹)	
		<u>North</u>	<u>South</u>	<u>North</u>	<u>South</u>
Spring	68	3332	3298	- 0.019	+ 0.017
Summer	35	2803	1970	- 0.016	- 0.023
Autumn	42	1754	2317	+ 0.020	- 0.059
Winter	42	1921	1653	+ 0.115	+ 0.006
		<u>9810</u>	<u>9238</u>		
Mean annual stocking rate (per 365 days)		26.9	25.3		
Mean stocking rate ha ⁻¹ **		12.4	8.9		

* Mean liveweight of grazing wethers approximately 35kg. Therefore equivalent to 0.6 stock units (S.U.) Actual stock numbers corrected by this factor.

** North aspect paddock area 2.17 ha; South aspect 2.83 ha⁻¹.

Appendix IV

Notes on pasture litter collected

1.10.75 to 1.10.76

The predominant form of litter at all times was grass-derived material. Only very small amounts of flat-weed litter and only a trace of legume material was collected despite the sometimes appreciable contributions they both made to total dry matter production (Table 3.4).

Campsites - In spring campsites were Poa annua and ryegrass dominant. Litter was comprised mainly of leaf and leaf sheath material shaded by the sward with most still attached to parent plants. In late spring, Poa annua was a major component of litter. More litter was trampled and more whole plants pulled out as grazing pressure increased.

Relatively high summer rainfall produced exceptional pasture growth which tended to become rank. Litter was derived mainly from shaded ryegrass. Very moist sward base conditions also produced a proliferation of aerial roots.

In early autumn collapsed stalk material formed the bulk of litter on both aspects. By late autumn vigorously growing pasture on the north aspect contained little litter. At this time the south aspect still contained many trampled stalks. Some uprooted Poa annua plants formed part of litter on both aspects.

Grass stalks continued to form litter on the south aspect until mid winter and from that time litter on both aspects was similar to that in spring.

25° and 45° sites - The more open sward on the slopes formed a more typical litter comprised of dead grass leaves with a higher proportion detached

from plants. Yorkshire Fog (Holcus lanatus) produced considerable leaf sheath litter where present and on the south aspect some moss was also included. As on campsites, more whole plants were uprooted as grazing pressure increased.

In summer paspalum sheath material made a significant contribution on some north aspect plots. In late summer the north aspect pasture was more mature than on the south and consequently more seed stems were present in litter. The top-soil was very dry and some pasture was killed by urine burn. Considerable pulling of whole plants occurred at higher grazing pressure during this time.

Stalk material predominated in litter during autumn but there was also more leaf and leaf sheath material than in summer. This was especially so with respect to paspalum on the north aspect.

Only following mid winter did stalk material cease to provide the main form of litter on both aspects and in later winter leaf material at the base of the sward again became the typical form of litter as in spring.

Appendix V Measurements at 15-30cm and 30-45cm depths of soil total P ($\mu\text{g g}^{-1}$), and water soluble inorganic P (DIP) and organic P (DOP) expressed as a percentage of TP. At the initial and final sampling dates only

Form of P	Stratum	North aspect				South aspect			
		1.10.75		1.9.76		1.10.75		1.10.76	
		15-30 (cm)	30-45 (cm)	15-30 (cm)	30-45 (cm)	15-30 (cm)	30-45 (cm)	15-30 (cm)	30-45 (cm)
Total P ($\mu\text{g g}^{-1}$)	Campsites	182	119	211	130	435	196	385	179
	25° slopes	128	101	136	109	162	141	168	137
	45° slopes	130	109	130	130	139	123	177	142
DIP (as % of TP)	Campsites	1.0	0.5	0.8	1.3	1.6	0.5	1.0	1.1
	25° slopes	0.6	0.7	0.8	0.8	0.2	0.4	1.0	0.7
	45° slopes	0.8	0.3	0.7	0.6	0.6	0.4	0.7	1.0
DOP (as % of TP)	Campsites	2.6	2.7	0.7	0.6	1.0	1.4	0.4	0.4
	25° slopes	2.3	3.5	1.0	0.8	2.3	2.0	0.8	0.6
	45° slopes	2.5	2.3	1.0	0.5	2.2	2.4	0.5	0.4

Appendix VI CSMP 73 MODEL OF LANGMUIR EQUATION
WITH PARAMETER EXAMPLES

```
TIMER FINTIM = 10.0, PRDEL = 0.100, DELT = 0.0001
PARAM K1 = 100.0, K2 = 1000.0, MAX = 1000.0, FILL = 206.1, VOL = 40.0,
      CONC = 32.6, LFILL = 0.00, LCONC = 0.0001
CONCD = CONC
FILLD = FILL
LFILLD = LFILL
LCONCD = LCONC
THETA = FILL/MAX
SORB = K1*CONC*(1-THETA)*DELT
DSORB = K2*THETA*DELT
LSORB = SORB*LCONC/CONC
LDSORB = DSORB*LFILL/FILL
CONC = CONCD + DSORB/VOL - SORB/VOL
FILL = FILLD + SORB - DSORB
LCONC = LCONC + LDSORB/VOL - LSORB/VOL
LFILL = LFILLD + LSORB - LDSORB
PRINT CONC, FILL, LCONC, LFILL
ENDJOB
```

Appendix VIINotes relating to determination of isotope
levels in plant and soil extracts

Discriminator channel settings for simultaneous reading of both ^{33}P and ^{32}P were 30-710 and 750-1000, respectively. Counting efficiency of each isotope at these settings was 64.3 and 80.9% for ^{33}P . At full width channel settings (0-1000) the counting efficiency was 95.2% for ^{32}P and 88.7% for ^{33}P . The ^{32}P carry over into the 30-710 range was equivalent to 17.3% of the total ^{32}P level. There was no carry over of ^{33}P into the ^{32}P channel.

The degree of quenching varied with the type of extract and isotope, e.g., efficiencies of ^{32}P and ^{33}P in a water extract from a north aspect campsite soil were measured at 92.5 and 73.8% respectively.

The corresponding values in an Olsen extract were 55.0 and 66.5%, respectively. These levels varied with aliquot size and soil sample, and were therefore necessarily redetermined for each series of experiments.

APPENDIX VIII

*
 FORTRAN PROGRAM FOR SIMULATING THE ABOVE-GROUND P CYCLE

```

C      *****
C      INPUT VARIABLES ARE AS FOLLOWS
C      *****
C      CAMPA=FRACTION OF AREA AS CAMPSITES
C      S25A =FRACTION AREA AS 25 SLOPES
C      S45A =FRACTION AREA AS 45 SLOPES
C      CAMPP=CAMPSITE PASTURE PROD. KG/HA
C      S25P =25 SLOPE PASTURE PROD. KG/HA
C      S45P =45 SLOPE PASTURE PROD. KG/HA
C      STOKR=STOCKING RATE UNITS/HA
C      PCONC=FRACTIONAL P CONC IN HERBAGE
C      UTC  =MAX PASTURE UTILN ON CAMPSITES
C      UT25 =MAX PASTURE UTILN ON 25 SLOPES
C      UT45 =MAX PASTURE UTILN ON 45 SLOPES
C      *****

      READ(5,10)CAMPA,S25A,S45A,CAMPP,S25P,S45P,STOKR,
10     1PCONC
      FORMAT(3(1X,F4.2),3I5,1X,F4.1,F6.4)
      CAMPRO=CAMPP*CAMPA
      S25PRO=S25P*S25A
      S45PRO=S45P*S45A
      TOTPRO=CAMPRO+S25PRO+S45PRO
      UPC=CAMPRO*UTC
      UP25=S25PRO*UT25
      UP45=S45PRO*UT45
      TUP=UPC+UP25+UP45
      UP=STOKR*550
      IF(TUP-UP)11,12,12
11     WRITE(6,13)
13     FORMAT(1H0,"YOUR STOCK ARE STARVING")
      GO TO 100
12     UPD=UPC+UP25
      IF(UPC-UP)14,16,16
16     XITC=CAMPRO-UP
      XIT25=S25PRO
      XIT45=S45PRO
      GO TO 17
14     IF(UPD-UP)18,15,15
C      *****
C      DUNG--DISTN DETAILS IN TEXT
C      *****
15     XITC=CAMPRO*(1-UTC)
      XIT25=S25PRO*(UP-UPC)
      XIT45=S45PRO
      GO TO 17
18     XITC=CAMPRO*(1-UTC)
      XIT25=S25PRO*(1-UT25)
      XIT45=S45PRO*(UP-UPC-UP25)
17     TDUNGP=PCONC*UP*0.9
      DUNG25=((S25PRO-XIT25)/UP)*0.45*TDUNGP
      DUNG45=((S45PRO-XIT45)/UP)*0.45*TDUNGP*0.5
      DUNG6C=0.55*TDUNGP+((CAMPRO-XITC)/UP)*0.45*TDUNGP

```

APPENDIX VIII CONTD.

```

1+DUNG45
PCUP=CAMPP*PCONC
PCLIT=(XITC*PCONC)/CAMPA
PCDU=DUNGC/CAMPA
21 IF(PCDU=100.0)20,20,21
XSC=PCDU-100.0
PCDU=100.0+.9*XSC
P25DU=DUNG25/S25A+.1*XSC*S25A/CAMPA
20 GO TD 22
22 P25DU=DUNG25/S25A
PTC=PCDU+PCLIT-PCUP
P25UP=S25P*PCONC
P25LIT=(XIT25*PCONC)/S25A
PT25=P25DU+P25LIT-P25UP
P45UP=S45P*PCONC
P45LIT=(XIT45*PCONC)/S45A
P45DU=DUNG45/S45A
PT45=P45DU+P45LIT-P45UP
WRITE(6,19)CAMPA,S25A,S45A,CAMPP,S25P,S45P,STOKR
1,PCONC,PCUP,PCLIT,PCDU,PTC,P25UP,P25LIT,P25DU
19 2,PT25,P45UP,P45LIT,P45DU,PT45
FORMAT(1H0,4X,"DISTRIBUTION OF STRATA",4X,"CAMP"
1,2X,F4.2,2X,"25DEGREE SLOPE",2X,F4.2,2X,"45 DE
3GREE SLOPE",2X,F4.2//1X,"PAST PRODUCTION OF
4STRATA",4X,"CAMP",1X,I5,2X,"25DEGREE SLOPE",1X,
5I5,2X,"45DEGREE SLOPE",1X,I5//10X,"STOCKING RATE"
6,5X,F4.1//10X,"P CONCENTRATION IN PASTURE",5X,
7F5.4//5X,"CAMP"/5X,"****"/15X,"P UPTAKE",F5.2,
8 5X,"LITTER RETURN",2X,F5.2,5X,"DUNG RETURN",2X,
9 F6.2,5X,"P TRANSFER",2X,F6.2//5X,"25DEGREE SLOPE
1"/5X,"****"/15X,"P UPTAKE",2X,F5.2,
2 5X,"LITTER RETURN",2X,F5.2,5X,"DUNG RETURN",2X,
3 F5.2,5X,"P TRANSFER",2X,F6.2//5X,"45DEGREE SLOPE
4"/5X,"****"/15X,"P UPTAKE",2X,F5.2,
5 5X,"LITTER RETURN",2X,F5.2,5X,"DUNG RETURN",2X,
6 F5.2,5X,"P TRANSFER",2X,F6.2)
100 RUSS=1
END

```

* Program Developed for Burroughs B6700 Computer.