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.

THE FATE OF POTASSIUM IN GRAZED DAIRY PASTURES

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

Prudence Helen Williams
1988

ABSTRACT

Losses of potassium (K) are inevitable in grazed New Zealand dairy pasture. Losses result from the removal of K in animal products, transfer of excreta to the dairy shed and raceways, and K leaching below the effective plant rooting zone. In this study the fate of K in a grazed dairy pasture was investigated in order to quantify the extent of these losses more precisely. As a consequence an improved methodology for predicting K fertiliser requirements has been developed.

A field experiment on the Tokomaru silt loam soil (yellow-grey earth) showed that immediately after a urination event in July up to 59% of the urine K moved preferentially through a network of soil macropores to below a soil depth of 15 cm. The remaining 41% of the urine K was retained in this depth of soil in the form of exchangeable soil K^+. Over the following spring and summer, plants were able to recover the urine K retained in the 0-15 cm depth of soil. The field experiment also showed that pasture plant roots growing in urine affected soil derived their K requirements mainly from the 0-15 cm depth of soil. Any K that moved beyond a depth of 15 cm due to leaching can be considered to be a loss of K from the grazed dairy pasture.

In a laboratory study, two soil types of contrasting mineralogy (the Tokomaru silt loam, a yellow-grey earth, and the Egmont brown loam, a yellow-brown loam) were incubated with either dairy cow urine or potassium chloride. Within 24 hours the soil pH in the urine treatment increased by one unit on both soil types. This increased soil pH was evident for 41 days in the Tokomaru soil and for the duration of the experiment (106 days) in the Egmont soil. For the Egmont soil, which contains larger amounts of pH dependent negative surface charge, this increase in soil pH resulted in greater K^+ adsorption by the soil from the urine treatment compared with the potassium chloride treatment. The Tokomaru soil contained smaller amounts of pH dependent charge, and there was no difference in K^+ adsorption between the two K sources. Such a result suggested that where potassium chloride solutions are used to simulate urine K additions to the soil, misleading results may occur. In the field, K^+ adsorption, and therefore leaching losses due to rainfall, from an application of urine may vary between soil types that differ in their surface charge characteristics.

The redistribution of urine K due to leaching, plant uptake and soil adsorption after an application of dairy cow urine to soil was investigated in two experiments with intact cores of four different soil types. In climatic conditions that simulated those of August/September in the

Manawatu region up to 80% of the urine moved preferentially beyond the 15 cm depth of soil. This preferential movement of urine occurred too quickly for adsorption reactions to occur between the soil surface and the solutes in the urine, therefore the soil type had little effect on the amount of urine K that was leached. After the urine application, sufficient simulated rain (as 6 events of 5 mm per day applied every second day over a 6-8 week period) was applied to produce 300 mm of drainage. Under free draining conditions the rainfall tended to move preferentially through the macropores of the soil cores bypassing the urine K in the soil, and so the amount leached was equivalent to 3-6% of the urine K applied. Where drainage was impeded, the rainfall moved less preferentially and more K (equivalent to 7-27% of the urine K applied) from the soil micropores was leached.

A technique was developed to measure the amount of urine K that was lost preferentially beyond the 15 cm depth of soil in the field situation. This technique was used on seven soil types, four of which were sampled in two different seasons. Results showed that between 0 and 46% of the urine K (and nitrogen) moved beyond the 15 cm depth due to preferential flow. These field results confirmed that preferential flow of urine through soil macropores resulted in the largest loss of K from all the soils studied. In general, the amount of K that was lost was more dependent on the physical conditions of the soil surface (e.g., water repellent or compacted soil surface, irregular surface microtopography) than the soil type or moisture content.

Data generated from this study were used to construct a model (the K Loss model) to predict the extent of K losses from three seasonal supply dairy farms. For one of the farms, on a peat soil, it was possible to show that the predictions of soil K losses made by the K Loss model were comparable with actual changes in soil K status. Similar evaluations on the other sites were impossible because the changes of soil K with time were insignificant in comparison with the native soil K contents.

Comparisons were made between the losses of K estimated by the K Loss model and the model used by the New Zealand Ministry of Agriculture and Fisheries in their Computerised Fertiliser Advisory Service (CFAS). The CFAS model did not account directly for the loss that occurs due to preferential flow of urine beyond the 15 cm depth of soil, although in some cases this loss can be considerable (e.g., 48 kg K ha^{-1} yr^{-1} on the Massey University No. 4 dairy farm). In addition the CFAS model appeared to overestimate the amount of K lost due to transfer of excreta to unproductive areas of the farm (e.g., the transfer loss was overestimated by 39 kg K ha^{-1} on the No. 4 dairy farm). More accurate predictions of the amounts of K lost,

and therefore the amounts of K fertiliser required to replace these losses, can be made easily using information supplied by the farmer from which the chronometric detail of the cows excretion pattern can be established.

ACKNOWLEDGEMENTS

I would like to express my gratitude to the following people for their contribution towards this thesis:

Dr Paul Gregg and Dr Mike Hedley for their supervision, guidance and patience during all stages of this project.

Past and present members of the Soil Science Department, particularly Dr Bolan, Dr Dave Scotter and Mr Russ Tillman, for advice, assistance and friendship throughout.

Mr Martin Eggels for technical assistance at different stages of the project.

The people who provided sites for the field trials and data for this study: staff of the Massey University No. 1, 3 and 4 dairy farms, staff of the Ministry of Agriculture and Fisheries Taranaki Agricultural Research Station, Mr Alan Gregg, Mr Paul Phippen, Mr Stuart Hamilton, Mr Ron Falconer, and the farmers who completed the questionnaire.

Dr Jacqueline Rowarth for her friendship and work in proof-reading and photocopying this thesis.

The Ministry of Agriculture and Fisheries for providing study leave which enabled this project to be carried out.

Finally, Lloyd Williams for his patience, support and encouragement throughout.

TABLE OF CONTENTS

ABSTRACT ii

ACKNOWLEDGMENTS v

TABLE OF CONTENTS vi

LIST OF FIGURES xiii

LIST OF TABLES xvii

CHAPTER 1

INTRODUCTION 1

CHAPTER 2

REVIEW OF LITERATURE

2.1 **INTRODUCTION** 4

2.2 **SOIL POTASSIUM** 6
- 2.2.1 **Structural Potassium** 6
- 2.2.2 **Nonexchangeable Potassium** 9
- 2.2.3 **Exchangeable Potassium** 11
- 2.2.4 **Soluble Potassium** 12
- 2.2.5 **Transformations of Soil Potassium** 12
- 2.2.6 **Conclusions** 14

2.3 **PLANT POTASSIUM** 14
- 2.3.1 **Pasture Dry Matter Yield** 14
- 2.3.2 **Concentration of Potassium In Pasture** 15
- 2.3.3 **Root Potassium** 16
- 2.3.4 **Conclusions** 16

2.4 **ANIMAL POTASSIUM** 16
- 2.4.1 **Conclusions** 17

2.5 **POTASSIUM GAINS** 18
- 2.5.1 **Potassium Fertiliser** 18
  - 2.5.1.1 *Form of potassium fertiliser* 19
- 2.5.2 **Potassium in Rainfall and Irrigation** 19
- 2.5.3 **Conclusions** 19

2.6 **TRANSFORMATIONS BETWEEN COMPARTMENTS** 20
- 2.6.1 **Plant Uptake of Soil Potassium** 20
  - 2.6.1.1 *Effect of species on plant uptake* 21
  - 2.6.1.2 *Effect of season on plant potassium uptake* 22
  - 2.6.1.3 *Effect of soil potassium status on plant potassium concentration* . 22
  - 2.6.1.4 *Measurement of plant available potassium* 23

2.6.2 **Return of Plant Potassium to the Soil** 25
  2.6.2.1 *Leaf leaching* 25
  2.6.2.2 *Plant and root decomposition* 25
2.6.3 **Return of Excretal Potassium to the Soil Pool** 26
  2.6.3.1 *Potassium concentration in excreta* 27
  2.6.3.2 *Number of excretions per day* 27
  2.6.3.3 *Size of each excretion* 27
  2.6.3.4 *Ground surface area covered by each excretion* 30
  2.6.3.5 *Total ground surface area covered by excreta* 30
  2.6.3.6 *Distribution of excretions between day and night* 32
2.6.4 **Fate of Excretal Potassium After Depostion on the Soil** 33
  2.6.4.1 *Urine potassium* 33
  2.6.4.2 *Dung potassium* 35
2.6.5 **Conclusions** 36

2.7 **POTASSIUM LOSSES** 36
2.7.1 **Loss of Soil Potassium Due to Leaching** 36
  2.7.1.1 *Effect of soil type, pH, rate and type of potassium fertiliser on potassium leaching* 37
  2.7.1.2 *Effect of experimental technique on estimates of potassium leaching* 39
2.7.2 **Loss of Potassium In Hay and Silage Crops** 42
2.7.3 **Loss of Animal Potassium** 42
  2.7.3.1 *Animal products* 42
  2.7.3.2 *Transfer of excretal potassium to unproductive areas* 43
  2.7.3.3 *Total animal loss of potassium* 43
2.7.4 **Conclusions** 45

2.8 **MODELLING OF POTASSIUM CYCLING** 46

2.9 **CONCLUSIONS** 50

CHAPTER 3

PLANT UPTAKE OF POTASSIUM FROM DIFFERENT DEPTHS OF URINE AFFECTED SOIL

3.1 **INTRODUCTION** 51
3.1.1 **Objectives** 52

3.2 **MATERIALS AND METHODS** 53
3.2.1 **Preliminary Investigations Into the Measurement of Rubidium In Soil and Plant Samples** 53
3.2.2 **Field Experiment** 55
  3.2.2.1 *Trial site* 55
  3.2.2.2 *Urine and rubidium chloride applications* 55
  3.2.2.3 *Herbage and soil sampling* 57
  3.2.2.4 *Measurement of the distribution of pasture root mass with depth* . 57
3.2.3 **Glasshouse Experiment** 57
3.2.4 **Herbage Analysis** 59
3.2.5 **Soil Analysis** 59
  3.2.5.1 *Exchangeable potassium and rubidium* 59
  3.2.5.2 *Soil pH* 59
  3.2.5.3 *Soil cation exchange capacity* 60

3.3 **RESULTS AND DISCUSSION** 60
  3.3.1 **Fate of Rubidium Injected Into the Soil** 60
    3.3.1.1 *Distribution in the soil* 60
    3.3.1.2 *Plant uptake* 63
  3.3.2 **Conclusions on Rubidium Data** 67
  3.3.3 **Fate of Urine Potassium Applied to Soil** 67
    3.3.3.1 *Retention in the soil* 67
    3.3.3.2 *Uptake by plants* 69
    3.3.3.3 *Influence of rainfall* 73

3.4 **CONCLUSIONS** 73

CHAPTER 4

POTASSIUM ADSORPTION BY SOIL AS INFLUENCED BY SOME SOIL CHARACTERISTICS AND THE FORM OF POTASSIUM

4.1 **INTRODUCTION** 75
  4.1.1 **Objectives** 75

4.2 **MATERIALS AND METHODS** 76
  4.2.1 **Soils** 76
  4.2.2 **Incubation Experiment** 76
  4.2.3 **Effect of pH on Potassium Adsorption** 78
  4.2.4 **Chemical Analysis** 78

4.3 **RESULTS AND DISCUSSION** 79
  4.3.1 **pH and Cation Adsorption** 79
  4.3.2 **Duration of pH Effect on Cation Adsorption** 91
  4.3.3 **Implications for Potassium Leaching** 92

4.4 **CONCLUSIONS** 92

CHAPTER 5

FATE OF DAIRY COW URINE APPLIED TO INTACT SOIL CORES

5.1 **INTRODUCTION** 94
  5.1.1 **Objectives** 95

5.2 **MATERIALS AND METHODS** 96
  5.2.1 **Establishment of Experiment** 96
    5.2.1.1 *Sites of soil collection* 96
    5.2.1.2 *Preparation of intact cores* 99
    5.2.1.3 *Experimental treatments* 101
  5.2.2 **Experiment Design** 101
    5.2.2.1 *Urine application* 101
    5.2.2.2 *Simulated rainfall* 101
  5.2.3 **Herbage Analysis** 103
  5.2.4 **Root Analysis** 103
  5.2.5 **Soil Analysis** 103

5.2.6 **Chemical Analysis** 103
    5.2.6.1 *Urine and leachate analysis* 103
    5.2.6.2 *Water soluble and exchangeable cations in soil* 104
5.2.7 **Statistical Analysis** 104
5.2.8 **Incubation Experiment** 105

5.3 RESULTS AND DISCUSSION 105
5.3.1 **The Fate of Urine Potassium In and the Overall Recovery of Potassium From the Soil Cores** 105
5.3.2 **Immediate Loss of Potassium From the Treatment Applications** 108
    5.3.2.1 *The influence of soil chemical and physical properties* 110
5.3.3 **The Leaching of Potassium During the Simulated Rain Events** 112
5.3.4 **Leaching of Other Ions** 114
    5.3.4.1 *Ammonium and chloride* 114
    5.3.4.2 *Magnesium, calcium and sodium* 114
    5.3.4.3 *Cation anion balance in the leachates* 117
5.3.5 **Herbage Yield** 120
5.3.6 **Uptake of Potassium By the Herbage** 122
5.3.7 **Uptake of Other Cations By the Herbage** 124
5.3.8 **Soil Analysis** 126

5.4 CONCLUSIONS 128

CHAPTER 6

PREFERENTIAL FLOW OF DAIRY COW URINE AND RAINFALL THROUGH INTACT SOIL CORES

6.1 INTRODUCTION 131
6.1.1 **Objectives** 132

6.2 MATERIALS AND METHODS 132
6.2.1 **Collection and Preparation of Soil Cores** 132
6.2.2 **Urine Application** 133
6.2.3 **Simulated Rainfall Applications** 133
6.2.4 **Final Simulated Rainfall Application** 135
6.2.5 **Herbage Analysis** 135
6.2.6 **Soil Analysis** 136
6.2.7 **Tritium Analysis In Leachate** 136
6.2.8 **Analysis of Exchangeable Ammonium In Soil** 136

6.3 RESULTS 138
6.3.1 **Measurement of the Time Taken to Collect Leachate from the Urine Application** 138
6.3.2 **Chemical Analysis of Leachates from Urine Application and Rainfall Events** 143
    6.3.2.1 *The radioactivity of tritium in the leachates* 143
    6.3.2.2 *Potassium concentration in the leachates* 145
    6.3.2.3 *Chloride, nitrogen and calcium concentration of the leachates* ... 145
6.3.3 **Leachate from the Final Rain Event** 153
6.3.4 **Soil Analysis** 155
6.3.5 **Potassium Balance** 159

6.4 DISCUSSION ... 161
  6.4.1 Preferential Flow of Urine Following Application ... 161
  6.4.2 Preferential Flow of Simulated Rain Events ... 167
  6.4.3 Potassium Leached from Simulated Rain Events ... 167
  6.4.4 Preferential Loss of Nitrogen and Other Elements Following a Urine Application ... 169
  6.4.5 Extrapolation of Results to the Field Situation ... 169

6.5 CONCLUSIONS ... 171

CHAPTER 7

PREFERENTIAL MOVEMENT OF DAIRY COW URINE FOLLOWING APPLICATION TO PASTURE UNDER FIELD CONDITIONS

7.1 INTRODUCTION ... 173
  7.1.1 Objectives ... 176

7.2 MATERIALS AND METHODS ... 176
  7.2.1 The Simulated Urine Event ... 176
  7.2.2 Measurement of Bromide and Recovery From Soil ... 178
    7.2.2.1 *Bromide analysis* ... 178
    7.2.2.2 *The evaluation of soil adsorption of the bromide* ... 178
  7.2.3 Field Experiments ... 180
    7.2.3.1 *First experiment* ... 180
    7.2.3.2 *Second experiment* ... 180
  7.2.4 Gravimetric Water Content Analysis ... 180
  7.2.5 Statistical Analysis ... 182
  7.2.6 Method Evaluation ... 182
    7.2.6.1 *Bromide recovery from soil* ... 182
    7.2.6.2 *Coring technique for field experiments* ... 182
  7.2.7 Variability of Field Observations ... 182

7.3 RESULTS AND DISCUSSION ... 184
  7.3.1 Effect of Soil Type and Season on Bromide Recovery ... 184
  7.3.2 Retention of Bromide on Other Soil Types ... 189
  7.3.3 Effect of the Distribution of the Potassium Bromide Solution Over the Soil Surface on the Amount of Bromide Recovered ... 189

7.4 GENERAL DISCUSSION ... 191

7.5 CONCLUSIONS ... 192

CHAPTER 8

MASS BALANCE MODELLING OF POTASSIUM LOSSES FROM THREE GRAZED DAIRY FARMS

8.1 INTRODUCTION ... 194
  8.1.1 Objectives ... 195
  8.1.2 General Site Information ... 195

8.2 **TARANAKI AGRICULTURAL RESEARCH STATION** 195
8.2.1 **Materials and Methods** 195
8.2.2 **Results and Discussion** 196
8.2.2.1 *Estimation of potassium losses from animal products* 196
8.2.2.2 *Estimation of losses from transfer of excretal potassium to unproductive areas* 200
8.2.2.3 *Estimated animal loss factor* 202
8.2.2.4 *Estimation of losses of potassium due to leaching* 202
8.2.2.5 *Comparison of the estimated changes in the net balance of potassium in the cycling pool with actual changes in soil potassium* 204

8.3 **WALLACE FARM** 207
8.3.1 **Materials and Methods** 207
8.3.1.1 *Measurement of the change in soil potassium status* 208
8.3.1.2 *Soil potassium, iron, phosphate contents and weight loss on ignition* 208
8.3.1.3 *Soil bulk density* 209
8.3.2 **Results and Discussion** 209
8.3.2.1 *Estimation of potassium losses from animal products* 209
8.3.2.2 *Estimation of losses from transfer of excretal potassium to unproductive areas* 209
8.3.2.3 *Estimation of losses of potassium due to preferential flow of urine* 211
8.3.2.4 *Estimation of losses of potassium due to leaching from rainfall* .. 211
8.3.2.5 *Gain in potassium from fertiliser* 212
8.3.2.6 *Change in soil potassium over the 30 year period* 212
8.3.2.7 *Comparison of estimated potassium losses with changes in soil potassium content* 215

8.4 **MASSEY UNIVERSITY No. 4 DAIRY FARM** 218
8.4.1 **Materials and Methods** 220
8.4.1.1 *Analysis of herbage potassium in excreta affected and nonaffected pasture* 220
8.4.2 **Development of the Model For the Soil-Plant-Animal System** 221
8.4.2.1 *Estimation of potassium ingested by the dairy cows* 221
8.4.2.2 *Loss of potassium due to animal products* 223
8.4.2.3 *Loss of potassium due to transfer of excreta to unproductive areas* 223
8.4.2.4 *Loss of potassium due to preferential flow of urine and leaching from rainfall* 225
8.4.3 **Discussion** 225

8.5 **GENERAL DISCUSSION** 227
8.5.1 **Reducing Potassium Losses on Dairy Farms** 227
8.5.1.1 *Loss of urine by preferential flow through soil macropores* 227
8.5.1.2 *Transfer of excreta to unproductive areas* 228
8.5.1.3 *Reducing the amount of potassium in excreta* 228
8.5.2 **Comparisons of Estimated Net Potassium Losses with Changes In Soil Potassium Content** 230
8.5.3 **Improvements to the CFAS Model** 231
8.5.3.1 *Losses of potassium due to animals* 232
8.5.3.2 *Herbage potassium* 233
8.5.3.3 *Contribution of soil potassium to the cycling potassium pool* 234

8.6 **CONCLUSIONS** 234

CHAPTER 9

SUMMARY 236

BIBLIOGRAPHY 241

APPENDICES 259

LIST OF FIGURES

Figure 2.1 Compartments and transformations of the K cycle in a fertilised, grazed pasture. 5

Figure 2.2 Forms of soil K and their interrelationships (Arnold, 1962; Sparks, 1987)........ 7

Figure 2.3 Schematic diagram of the positions of K found in micaceous minerals (Rich, 1968). 10

Figure 2.4 Types of breakthrough curve for a pulse of solute moving through a column of saturated soils: piston-type flow (—): preferential flow (--). 40

Figure 3.1 The distribution of exchangeable Rb^+ in soil cores immediately after the injection of 3.3×10^{-3}M RbCl at the (a) 0-2.5, (b) 0-14.5 and (c) 12-14.5 cm soil depths. 61

Figure 3.2 Herbage dry matter yield (●) and herbage K^+ concentration (○) at each harvest date. Values are means for all treatments (i.e., 18 replicates in August decreasing to 3 replicates in March). The K^+ concentration of herbage from areas not affected by urine is also presented (□) 65

Figure 3.3 Exchangeable soil K^+ and cumulative herbage K at each harvest. 68

Figure 4.1 Soil pH before (▲) and after incubation with urine (■) or KCl (●). Values are means of duplicate experimental units (mean deviation <2% except for final point of Tokomaru KCl treatment data which showed a 3% mean deviation). 80

Figure 4.2 The amount of 1M NaCl extractable NH_4^+ (adsorbed) in soil incubated with urine (■) or KCl (●). Values are means of duplicate experimental units (mean deviation Tokomaru soil <15%, and Egmont <25%) 81

Figure 4.3 The amount of water soluble NH_4^+ extracted from soil incubated with urine (■) or KCl (●). Values are means of duplicate experimental units (mean deviation <25%). 82

Figure 4.4 Soil pH buffer curves for Tokomaru (□) and Egmont (▼) soils. Values are means of duplicate experimental units (mean deviation <5%). 83

Figure 4.5 The amount of water soluble NO_3^- extracted from soil incubated with either urine (■) or KCl (●). Values are means of duplicate experimental units (mean deviation <10%). 84

Figure 4.6 The amount of Na^+ adsorbed from a solution of 1M NaCl by soil previously incubated with urine (■) or KCl (●). Values are means of duplicate experimental units (mean deviation <10%) 86

Figure 4.7 The amount of water soluble K^+ extracted from soil before (▲) and after incubation with urine (■) or KCl (●). Values are means of duplicate experimental units (mean deviation <10%). 87

Figure 4.8 The relationship between pH and the ratio of water soluble K^+ : adsorbed K^+ in soils treated with urine (■) and KCl (●). Values are means of duplicate experimental units (mean deviation <10%) 88

Figure 4.9 Effect of changing soil pH, through incubation with either sulphuric acid or ammonium hydroxide, on the distribution of natural soil K between water soluble K^+ and adsorbed K^+. Values are means of duplicate experimental units (mean deviation <10%). 90

Figure 5.1 A diagrammatic representation (not to scale) of the system used to collect leachate from the inner area A (154 cm^2 in the 14 cm diameter plastic container) and the outer area B (23 cm^2 in the 20 cm diameter plastic container) of the soil cores 100

Figure 5.2 The amounts of leachate, soil and plant K present following the application of urine of different concentrations to intact cores of different soil types. The amounts of K are expressed using the formula [(K in urine treated soil - K in water treated soil) x 100 / K applied in urine]. Values are means of six replicates except for the data for the amount of K in roots which are based on two replicates. 107

Figure 5.3 The percentages of applied K recovered as the sum of water soluble plus exchangeable soil K^+ immediately after (day 0) and at 30 days after the incubation of four different soils with urine or KCl. Values are means of two replicates. 109

Figure 5.4 The relationship between the amount of leachate collected and the amount of K collected in the leachate during a three day period following an application of dairy cow urine to intact cores of four different soil types. The data points represent the mean values for each soil type (Tokomaru (▽), Manawatu (△), Egmont (○), Pukepuke (□)) and urine treatment (low urine (closed symbols), high urine (open symbols)). Values are means of six replicates. 111

Figure 5.5 The amounts of K leached during each rain event from cores which received the low (●) and high (○) urine treatments. SEDs for all soil types and urine concentrations are presented in Figure 5.5b. Values are means of six replicates. 113

Figure 5.6 The sum of the amounts of Mg and Ca in the leachates collected immediatly after the urine application (■) and the rain events for each soil type. Values are means of six replicates. 115

Figure 5.7 The amounts of nitrate leached from cores of different soil types (Tokomaru (▽), Manawatu (△), Egmont (○) and Pukepuke (□)) and urine treatments (water (×), low urine (closed symbols), high urine (open symbols)). SEDs for all soil types and urine concentrations are presented in Figure 5.7a. Values are means of six replicates. 118

Figure 5.8 Sum of cations ($\Sigma(K^+, NH_4^+, Mg^{++}, Ca^{++})$;●) and anions ($\Sigma(NO_3^-, Cl^-)$;■) collected in the leachate from each rain event. Values are means of six replicates. 119

Figure 5.9 The dry matter yield of clover, grass and total herbage on cores of the four different soil types. Values are means of six replicates. 121

Figure 5.10 The K^+ concentration in the herbage (clover and grass) and the total amount of K recovered in the herbage from cores of the four different soil types. Values are means of six replicates. 123

Figure 5.11 The gain in the amount of water soluble and exchangeable K^+ in the four soils, expressed as the difference in amount of K before and after the experiment. Values are means of six replicates. 127

Figure 6.1 The relationship between H-number and counting efficiency of tritium in samples of leachate. 137

Figure 6.2 The length of time taken to collect 25 g aliquots of leachate following on application of dairy cow urine to intact soil cores 139

Figure 6.3 The relationship between the relative activity (C/Co) of tritium in the first 25 g of leachate collected after an application of tritium labelled dairy cow urine to intact soil cores and the time taken to collect that leachate (numbers on diagram represent core numbers). 141

Figure 6.4 Breakthrough curves of tritium for fast draining (X) and slow draining (O) cores after the application of 200 ml of dairy cow urine and sufficient simulated rainfall to produce approximately 300 ml of drainage (equivalent to 2.4-4.6 pore volumes). 144

Figure 6.5 Breakthrough curves of K for fast draining (X) and slow draining (O) cores after the application of 200 ml of dairy cow urine and sufficient simulated rainfall to produce approximately 300 ml of drainage (equivalent to 2.4-4.6 pore volumes). 147

Figure 6.6 The accumulated amount of NO_3^--N leached from fast draining (X) and slow draining (O) cores after the application of 200 ml of dairy cow urine and sufficient simulated rainfall to produce approximately 300 ml of drainage (equivalent to 2.4-4.6 pore volumes). 151

Figure 6.7 The gain in water soluble K^+ and exchangeable K^+ in soil cores after the application of urine and simulated rainfall (i.e., K content [amended soil - original soil]) 156

Figure 6.8 The gain in KCl-extractable soil NH_4^+-N in soil cores after the application of urine and simulated rainfall (i.e., NH_4^+-N content [amended soil - original soil]). 157

Figure 6.9 The relationship between change in soil pH and the difference between the total amounts of NH_4^+-N and NO_3^--N produced in and leached from fast (open symbols) and slow (closed symbols) draining intact cores of Tokomaru (▽), Manawatu (△), Egmont (○) and Pukepuke (□) soil. 160

Figure 6.10 The amounts of leachate, soil and plant K present following an application of cow urine to intact cores of different soil types. The amounts of K are expressed as a % of the amount of urine K applied. 162

Figure 6.11 The relationship between the proportion of tritium leached and the proportion of (a) K, (b) total N and (c) Cl leached immediately after the application of tritium labelled dairy cow urine to intact cores of Tokomaru (▽), Manawatu (△), Egmont (○) and Pukepuke (□) soil. 164

Figure 6.12 The effect of drainage on the relative activity of tritium (X) and concentration of K^+ (O) in the leachate from fast and slow draining cores. Only data for the Pukepuke (—) and Egmont (- -) soil types are presented. 166

Figure 7.1 A diagrammatic representation of the grid used to collect soil cores and the volume of the cores in relation to the volume of soil represented by each core 177

Figure 7.2 The mean recovery of Br from the 0-15 cm depth of seven soils after urine deposition on pasture was simulated using KBr solution........ 185

Figure 7.3 The distribution of methylene blue dye through soil macropores created by plant roots and earthworms in the Manawatu silt loam following a simulated urination event of 2 dm^3 of dye applied to the soil surface in May 1987. 186

Figure 7.4 The distribution of methylene blue dye through soil macropores created by soil fracture planes in the Tokomaru silt loam following a simulated urination event of 2 dm^3 of dye applied to the soil surface in March 1987. 186

Figure 7.5 The distribution of methylene blue dye through soil macropores created by plant roots and grassgrub channels in the Egmont brown loam following a simulated urination event of 2 dm^3 of dye applied to the soil surface in May 1987........ 187

Figure 7.6 The distribution of methylene blue dye through soil macropores created by plant roots in the Pukepuke black sandy loam following a simulated urination event of 2 dm^3 of dye applied to the soil surface in March 1987........ 187

Figure 7.7 Relationship between area covered by the applied KBr and Br recovery (%) in the 0-15 cm soil depth of seven soils........ 190

Figure 8.1 The amounts of potassium, iron and phosphate in, and the weight loss on ignition of soil from different depths of undeveloped and developed peat on the Wallace farm........ 214

Figure 8.2 A model of net transfers of potassium on the Massey University No. 4 dairy farm (kg K ha^{-1})........ 224

LIST OF TABLES

Table 2.1 Total and exchangeable K content (me $100g^{-1}$) of major dairy farming soils in New Zealand (data from Metson, 1980). 13

Table 2.2 Concentration of K in dairy cow urine (% of wet weight) and dung (% of dry weight). 28

Table 2.3 Mean number of urinations and defaecations per 24 hours by cattle. 29

Table 2.4 Mean volume of a single urination and wet weight of a single defaecation for cows. 29

Table 2.5 Ground surface area covered by individual urinations and defaecations. 31

Table 2.6 Fate of urine potassium as a % of that applied in laboratory and field experiments. 34

Table 2.7 Percentage of daily urinations and defaecations that are deposited in the milking shed and raceways by dairy cows. 44

Table 3.1a The measured concentration of Rb ($\mu g\ ml^{-1}$) in herbage digests and 1M ammonium acetate soil extracts containing various K concentrations. The herbage digests and soil extracts were spiked with either 0 or 1 $\mu g\ ml^{-1}$ Rb. Values are means of duplicate experimental units (mean deviation <8%). 54

Table 3.1b As for Table 3.1a, but all digests and extracts were diluted twenty times. Further details are given in the text (section 3.2.1) 54

Table 3.2 Background information on the Tokomaru silt loam. 56

Table 3.3 The volume of solution and amount of Rb injected into the soil for each treatment. 56

Table 3.4 The amounts of exchangeable Rb^+ extracted from soil at various harvest dates after the injection of 3.3×10^{-3}M RbCl at 0-2.5, 0-14.5 and 12-14.5 cm soil depths. Values are of one replicate only. 62

Table 3.5 The amounts of Rb taken up by the herbage at each harvest date after the injection of 3.3×10^{-3}M RbCl at 0-2.5, 0-14.5 and 12-14.5 cm soil depths. 64

Table 3.6 The distribution of pasture root mass in the Tokomaru silt loam. 66

Table 3.7 The amount of rainfall, number of rainy days, and amount of predicted drainage during the field trial. Data collected from the DSIR, Palmerston North and D.J. Horne (pers. comm.). 66

Table 3.8 The ratio of the amount of K absorbed by plant roots (as measured by the change in soil exchangeable K^+ during the experiment) to the weight of roots at each soil depth. 72

Table 4.1 Taxonomic details and some characteristics of the Tokomaru silt loam and the Egmont brown loam. 77

Table 4.2 Chemical analysis of dairy cow urine and KCl solution. 77

Table 5.1 Some physical and chemical characteristics of the 0-7.5 cm depth of the soils used. The methods used to measure soil pH, CEC and exchangeable K^+ are described in sections 3.2.5.2, 3.2.5.3, 5.2.6.2. 97

Table 5.2 The locations and the background information on the sites from which the soils were collected.. 98

Table 5.3 The chemical composition of the urine samples (for methods of analysis see section 5.2.6.1). 102

Table 5.4 The amounts of leachate, soil and plant K measured following the application of urine of different concentrations (water, low and high K concentration) to intact cores of different soils (mg K $core^{-1}$). 106

Table 5.5 The sum of the water soluble and the exchangeable cations in all four soils before and after the experiment for soil cores receiving urine of low and high concentrations (0-15 cm depth of soil; me 100 g^{-1}). 116

Table 5.6 The mean K/(Ca+Mg) ratios in the herbage (sum of clover and grass fractions).. 125

Table 5.7 The mean soil pH at the end of the experiment (0-7.5 cm depth). 129

Table 6.1 The chemical composition of the urine (methods of analysis are detailed in sections 5.2.6.1 and 6.2.7). 134

Table 6.2 The analysis of variance table for the time (seconds) taken to collect 100 g of leachate (5.6 mm of drainage) from cores of four different soil types........... 140

Table 6.3 The percentage of applied tritium that was leached from soil cores immediately following the urine application and during the simulated rain events............ 146

Table 6.4 The amounts of K leached from soil cores immediately following the urine application and during the simulated rain events (expressed as mg K $core^{-1}$ and % of urine K applied). 148

Table 6.5 The amounts and forms of N leached from soil cores immediately following the urine application (mg N $core^{-1}$). 150

Table 6.6 The amounts of Ca leached from soil cores immediately following the urine application and the simulated rain events (expressed as mg Ca per $core^{-1}$ and as a % of the amount of exchangeable Ca initially present in the soil)......... 152

Table 6.7 The relative activity (C/Co) of tritium in the first 25 g of leachate collected after the original urine application, and after the application of the final rain event.. 154

Table 6.8 Soil pH before and after the experiment (mean of all depths). 158

Table 6.9 Regression equations for the relationship between the % tritium (^3H) leached and the % K, Cl and N leached immediately following the urine application. 165

Table 7.1 Some properties of the soils used in the first field experiment. Details of soil classification, bulk density, site location etc. are given in Tables 5.1 and 5.2. 174

Table 7.2 The soil gravimetric moisture content at time of sampling (g g^{-1}). 179

Table 7.3 Some properties of the soils used in the second field experiment. 181

Table 7.4 The recovery of applied Br from 4 soils after laboratory incubation. 183

Table 7.5 The effect of the number of cores (25, 50 or 100) taken from the same 75 cm x 75 cm area on the estimate of Br retention in field soils. 183

Table 8.1 Production data from the farmlet on the Taranaki Agricultural Research Station. 197

Table 8.2 Estimates of the amount of K removed in animal products calculated from the production data (Table 8.1) on the Taranaki Agricultural Research Station. 198

Table 8.3 Estimates of the amount of K removed in animal products calculated from the pasture intake data on the Taranaki Agricultural Research Station. 199

Table 8.4 Estimates of the amount of K lost through deposition of excreta off the paddock in the dairy shed and raceways on the Taranaki Agricultural Research Station. 201

Table 8.5 Estimates of the amount of K leached from preferential movement of dairy cow urine after deposition on the paddock, and from rainfall on the Taranaki Agricultural Research Station. 203

Table 8.6 The predicted amount of annual animal K loss (ALF) for the whole farmlet using ALF factors of both 1.6 and 4.0 kg K su^{-1}, and the amount of annual K gain due to fertiliser application on the Taranaki Agricultural Research Station. 205

Table 8.7 The predicted total amount of K lost for the whole farmlet from both animal production and leaching using an annual animal loss factor (ALF) of 1.6 (for animal losses due to production and transfer) and the amount of annual K gain due to fertiliser application on the Taranaki Agricultural Research Station (kg K $farmlet^{-1}$). 205

Table 8.8 MAF Quick test K results for the Taranaki Agricultural Research Station (mean for all paddocks on the farmlet; MAF Quick test units; 0-7.5cm depth of soil). 206

Table 8.9 Production data, the estimated amount of K lost due to animal production and transfer to unproductive areas, and the estimated amount of urine K lost due to preferential flow of dairy cow urine beyond the effective plant root zone on the Wallace farm. 210

Table 8.10 Fertiliser history for the Wallace farm. 213

Table 8.11 The predicted amounts of K lost from, and gained to the Wallace farm, calculated using production data (Table 8.9) and the K Loss model (Appendix VIIc). 216

Table 8.12 The predicted amounts of K lost from, and gained on the Wallace farm, calculated from the CFAS model. (Details of equations and abbreviations in section 2.8). 217

Table 8.13 Estimation of the animal loss factor due to animal production and transfer of excreta to unproductive areas on the Wallace farm. 219

Table 8.14 Calculation of annual stock population density for the No.4 dairy farm (cows ha^{-1}). 222

Table 8.15 The concentration of K in herbage cut to ground level before and after grazing from both excreta affected and non-affected pasture (%K). 222

Table 8.16 Effect of reducing the herbage K concentration on K intake and K losses for the Wallace farm (kg K cow^{-1} yr^{-1}). 229