Chapter 7. Evaluating the Performance of the EMU Model

Some authors suggest that models cannot generate knowledge or information (Grayson & Chiew 1994), they can be used to investigate system behaviour as a function of different management practices. Before a model can be used as an investigative tool it is important to perform tests to determine the level of confidence that can be placed in the model output. This chapter presents the last step in developing the model and evaluates the EMU model output.

The four cations (Na, K, Mg and Al) and N and P were compartmentalised into three output pathways of runoff, drainage and crop uptake. A daily mass balance of each cation and nutrient is calculated, assuming the flow of soil water is the means of transporting the nutrients through each compartment. This flow of soil water is based on a tipping bucket principle. When evaluating the performance of the model it is important to consider that the EMU model is concerned with the relative magnitude of the output pathways and not with exactly replicating the processes occurring in the utilisation system.

Even though a mass balance approach is taken in the development of the EMU model, it is necessary to incorporate some limited process models in the form of the cation exchange module. This exchange module provides a mechanism for the transfer of soluble and adsorbed forms of the cations in the soil. A limitation of this cation exchange module is that is has not been calibrated, verified and validated, which would increase the degree of confidence in using the model. Calibration of the cation exchange module is required over a range of soil moisture conditions and this task is outside the scope of this study. However, the nutrients removed in each output pathway modelled are compared with measured data in the following sections.

Simple input/output models are not as difficult to evaluate as distributed parameter models. These simple models do not require examination of diagnostic plots, which are necessary to reveal the performance of the internal operations of a distributed parameter model (Grayson & Nathan 1993). It is also desirable that as many model parameters as possible are estimated from measurable properties of the system being modelled (Sivapalan *et al.* 1996).

Ideally the evaluation of the model would require three steps. The first step in the evaluation phase is the calibration of model parameters that cannot be measured or estimated from field data, using one dataset. The normal approach for this is to minimise the error between the predicted and measured values by adjusting the parameter set, either manually or using an automatic procedure. This can lead to the optimal values for the parameters, however different parameter sets may produce similar results (Pinol *et al.* 1997). Verifying the chosen parameter set with a second dataset is the method generally used in the next step of model evaluation. Finally, validation of the model is achieved by comparing the analytical solution with the modelling results. Availability of limited data has led to a modified procedure in evaluating the EMU model, with the goal being to minimise the arbitrary fitting of the model (Bassett 1997).

An evaluation of a simple mass balance model generally only requires the measurement of two points, which are then compared with the model output (Bassett 1997). This is in contrast to the calibration, verification and validation requirements of physically based process models. Some 'tweaking' of the minimal input parameters in the EMU model is carried out in order that the output from the model is more representative of the measured output data collected from the Tullimba feedlot to date. When comparing these values, the heterogeneity of the modelled area is considered and the requirement for evaluating the performance of the EMU model is for the simulated output to be within the same order of magnitude of the measured data.

7.1 Adjustment of the Model Parameters

It is normal practice for hydrological models to be initially calibrated using the water balance alone to assess whether the hydrological mass transfer compares with measured rainfall and runoff data (Bassett 1997). A San Dimas flume was in place to measure the runoff from the irrigation area over the course of the study. This flume was situated below the terminal pond by-wash level and when the terminal pond was full, the flume was flooded and not able to measure the flow. This has been addressed by inserting a V-notch weir in the flume, but the results to date are minimal and therefore USDA SCS rainfall-runoff model output is used for the calibration of the hydrological component. The USDA SCS curve method is used because of its wide use in hydrological studies, and its minimal data input requirement (Faulkner, R. 1999, pers. comm., 12 Jan).

There are considerable difficulties associated with the calibration of hydro-geochemical models (see Pinol *et al.* 1997 for a discussion of these difficulties) and some researchers have found that to calibrate some models, unrealistic values of model parameters have to be used (Grayson & Nathan 1993). Therefore, to make the model user friendly, parameters requiring calibration are minimised within the model.

The inputs to the model of cropping cycles, fertiliser, manure and effluent application regimes are selected from bay 5 in the northern irrigation block, which is at the top of the slope. The cumulative runoff generated by the USDA SCS curve method is compared with the simulated runoff using actual rainfall data, and the hydraulic conductivity, field capacity, saturation and wilting points of the three soil layers are adjusted. This adjustment is based on using realistic values for the soil moisture parameters and is carried out until the error between the simulated and USDA SCS curve method data is minimised, by subjectively comparing the cumulative runoff from both methods.

The factors governing the generation of surface runoff are soil type, land use, crop and management, antecedent conditions, infiltration rate and soil moisture content (Morgan 1995; USDA SCS 1986). The USDA SCS Runoff Curve Number method generates runoff as a function of these elements and is used to check if the EMU model can replicate the runoff produced by the USDA method.

The USDA SCS Runoff Curve Number (N) is determined from tabulated values and for a moderately fine to fine textured soil with slow permeability, growing small grains, N should be around 74-78 (USDA SCS 1986). Runoff is calculated as a function of rainfall from Equation 7.1 and Equation 7.2.

$$R = \frac{(P - 0.2S)^2}{P + 0.8S} \quad \text{.......... Equation 7.1}$$

$$S = \frac{25400}{N} - 254 \quad \text{.......... Equation 7.2}$$

where

N is the USDA SCS Runoff Curve Number,

R = runoff (mm), and

P = precipitation (mm).

Using the values for soil moisture characteristics as a function of texture, the EMU model underestimates the runoff when compared with the values produced by the USDA SCS curve method (N=76). To calibrate the soil moisture parameters, the runoff events generated by the USDA SCS method are used to investigate the saturated hydraulic conductivity and soil moisture parameters that would lead to approximately the same runoff in the EMU model. The values that produced the best output when compared with USDA runoff, are shown in Table 7.1. The comparison of the simulated runoff with the runoff produced by the USDA SCS method is shown in Figure 7.1.

Table 7.1. Calibrated Soil Moisture Characteristics

Horizon	Wilting Point (mm)	Field Capacity (mm)	Saturated Moisture Content (mm)	Saturated Hydraulic Conductivity (mm/day)
A1	15	30	50	20
A2	31	53	106	20
B	59	76	153	15

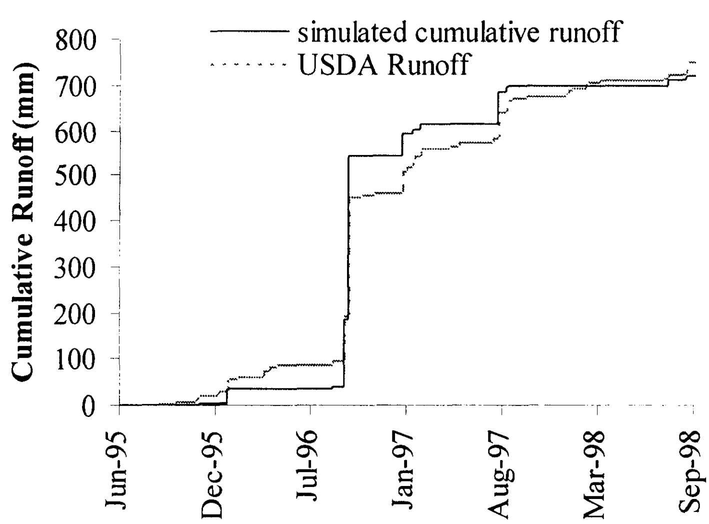


Figure 7.1. Comparison of Cumulative Runoff Produced by the Runoff Curve Number Method and the Simulation Model

The saturated hydraulic conductivities which produced similar runoff results between the EMU model and the USDA SCS curve method are considerably lower than those recommended by the use of the SOILPAR model (see Section 6.6.1). These lower hydraulic conductivities of 20 mm/day in the A1 and A2 horizon and 15 mm/day in the B horizon are supported by data collected before the Tullimba feedlot began operation. Infiltrometer measurements taken in the irrigation area suggest that surface infiltration rates (ring infiltrometer) are of the order of 1-7 mm/hr and intake rates in the B-horizon (Talsma Tube) are of the order of 1-3 mm/hr (Aquila Agribusiness Pty Limited 1993).

As previously mentioned, the nutrient processes in the model are not calibrated in this study, however to increase the confidence in the use of the model as a management tool, an evaluation of some of the model output against measured data is included. The two datasets used for this evaluation are:

- EC of the ground water from a piezometer (P27) in the irrigation area compared with the simulated drainage EC; and
- concentrations in the runoff from the irrigation area (terminal pond) compared with the simulated concentrations.

7.1.1 Comparison of Simulated Drainage EC With Measured Ground Water EC

It is difficult to verify if the quantities of nutrient removed in drainage are modelled correctly. While the EC of the ground water provides an indication of the gross amount of nutrients present, it does not indicate the percentage of each nutrient. Using the concentration of each element to determine the gross amount of each element present is also complicated by the size of the aquifer being unknown. Another complication is introduced by the variation in the ground water samples collected from the irrigation area, as indicated by the time series of the EC measurement taken from two piezometers in the irrigation area, shown in Figure 7.2. The two piezometers included in Figure 7.2 are located in the northern half of the irrigation area approximately 100 m apart on a west east transect, with P27 down gradient of P25. The different characteristics of the ground water at these two points indicates the difficulties faced when attempting to evaluate the model output, which is also included in Figure 7.2.

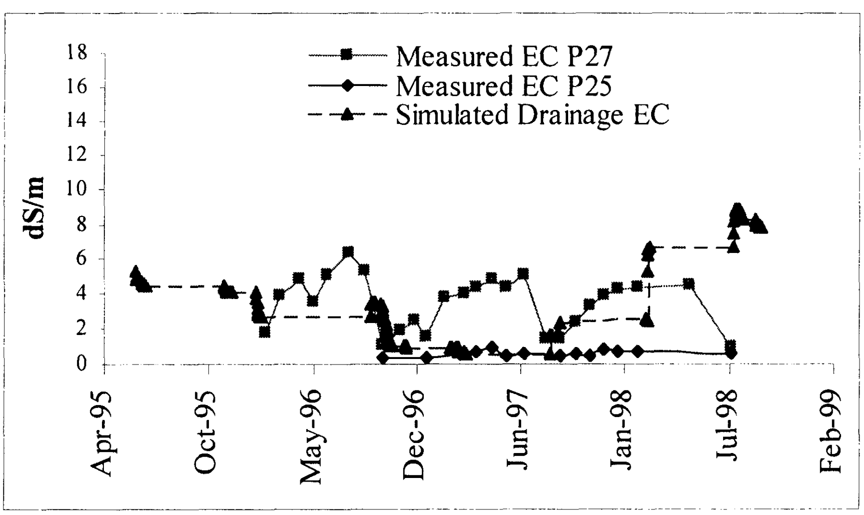


Figure 7.2. Comparison of Measured EC in P27 and P25 and Simulated Drainage

7.1.2 Comparison of Simulated and Measured Runoff Quality

Samples were taken from the terminal pond on a monthly basis and only a few runoff samples from the irrigation area were obtained. Therefore, simulated runoff concentrations are compared with concentrations in the terminal pond over the simulated time period, shown in Figure 7.3. These graphs indicate the simulated runoff concentrations are generally within the same order of magnitude of those measured, except for a large variation in the inorganic N and ortho-P concentrations. Because of the volatility of inorganic N, it is conceivable that monthly sampling of the terminal pond could have missed large short-lived increases in inorganic N concentration. In the case of ortho-P, it is likely that this element would precipitate out, and as monthly effluent analyses were done on filtered samples, the values measured are those in solution only. Further evaluation of the model will be carried out by using input data from another irrigation bay and comparing the simulated output with collected soil and crop data.

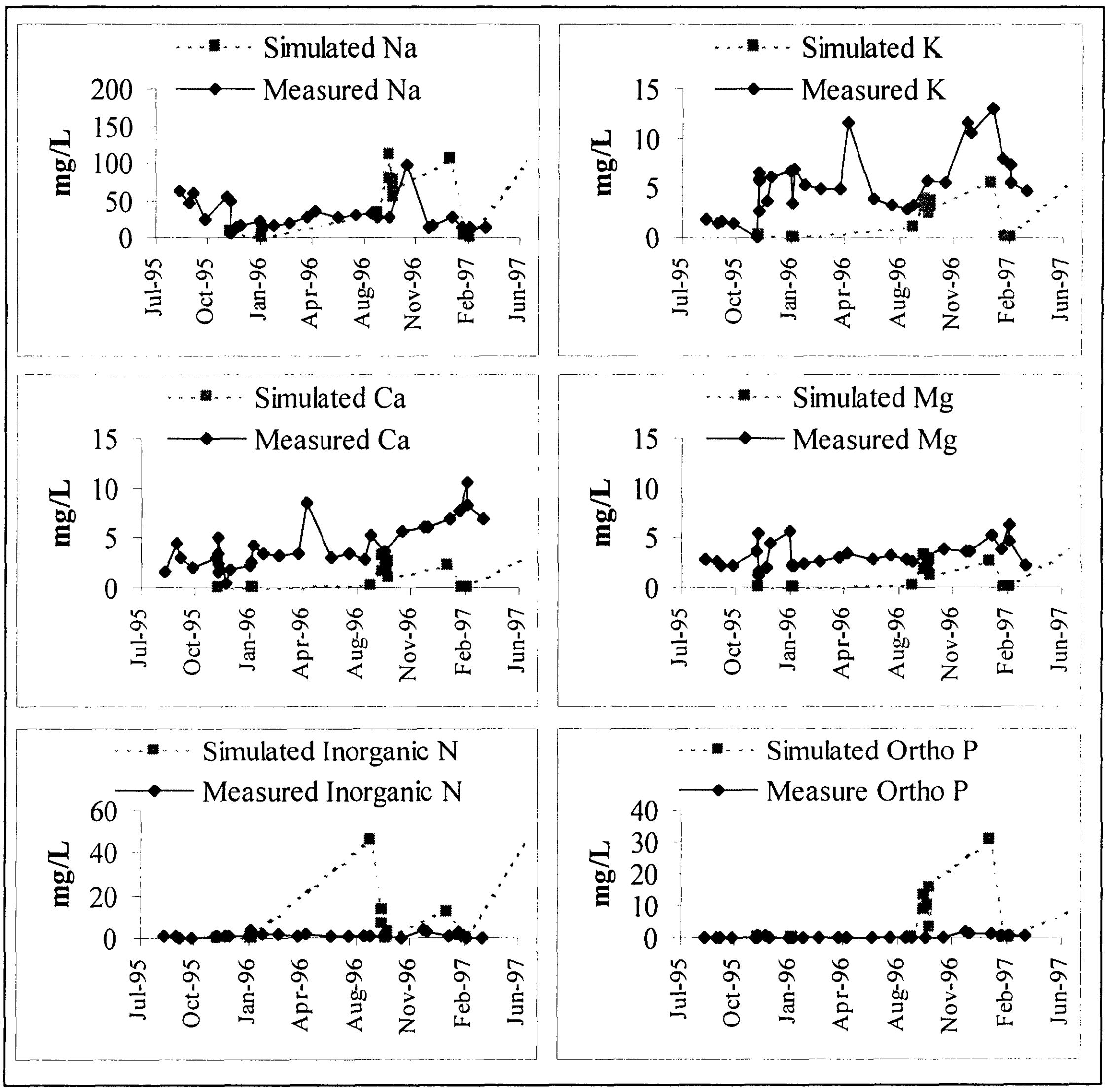


Figure 7.3. Comparison of Simulated Runoff Concentrations with Terminal Pond Concentrations Over the Simulation Period

7.2 Further Evaluation and Testing of Model Output

The objective of the modelling exercise was not to be able to accurately model the interactions occurring in the soil, but to model the output pathways. Collected field data are averaged and used to compare with simulated results to verify that soil nutrients predicted by the EMU model are reasonable estimates when evaluated against available data (Young 1977). The method relies on a 'snapshot' description of the simulated mass of each nutrient on two days and compares with those measured in the field on the same two days (Bassett 1997).

7.2.1 Comparison of Simulated and Measured Nutrients in the Soil

To verify that the changes in the soil store are being modelled to a reasonable degree, a simulation is conducted using data from bay 5 on the southern side of the irrigation area. This bay had no manure applied over the 3.5 years simulated, but the use of inorganic fertiliser and the cropping regime was the same as for bay 5 on the northern side of the irrigation area. There is limited data available to compare the soil data results from this run using time series bases, as there were only two sampling dates from this irrigation bay over the previous three years. These sampling points are used to compare the soil concentrations with those estimated by the EMU model on the same two days. As Figure 7.4 and Figure 7.5 show, the model under predicts on the 11th March 1996 for Ca, and for total P in the A1 and B horizon. It then over predicts these parameters on the 4th March 1997.

There is considerable variation in the soil measurements taken over the course of the study for each of the nutrients included in the EMU model (Appendix E and see Friesen and Blair (1984) for a discussion of sampling methods to minimise data variation). The measured values used for the comparison with the simulated values represent measurements for two specific locations and times, and 'homogeneity most certainly is a poor assumption over the expanse of any watershed' (Basset 1997). Given this variation, the predicted versus measured values are considered sufficient in that the model is not trying to accurately replicate the processes occurring within the soil system, but rather represent the relative movement of the nutrients through each of the pathways. Output from this model is required to be within the same order of magnitude of the variation observed in the measured data and this is evident from Figure 7.4 and Figure 7.5.

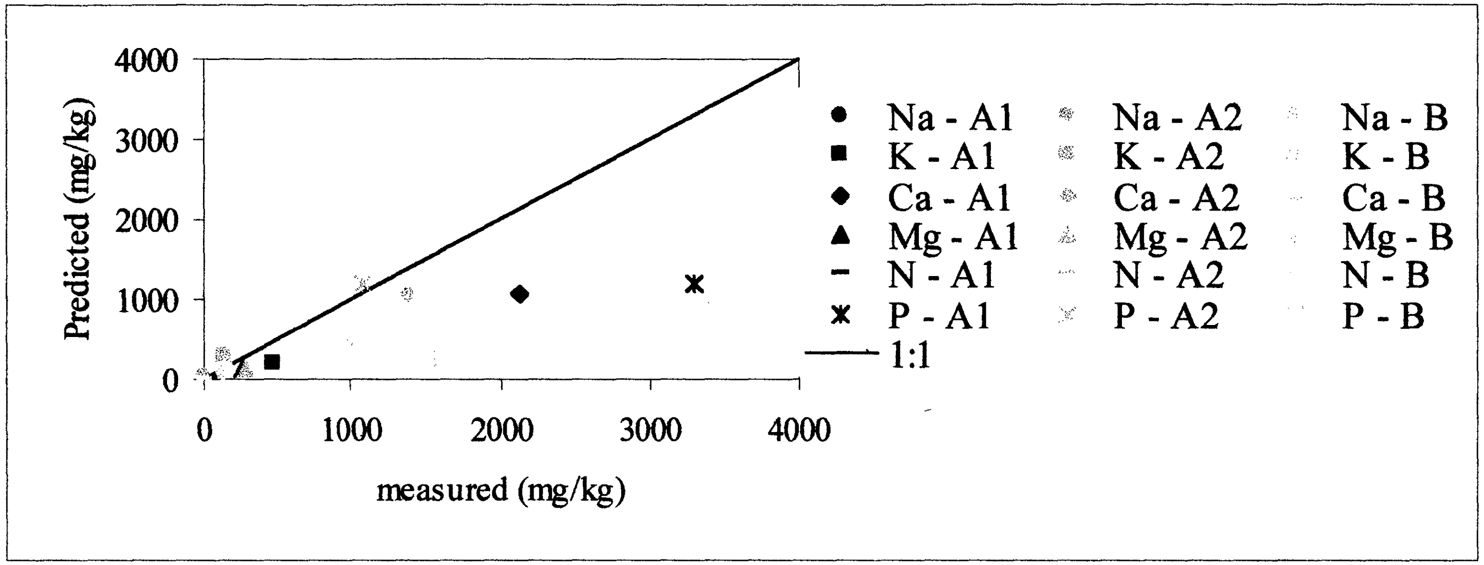


Figure 7.4. Predicted and Measured Values for 11Mar96

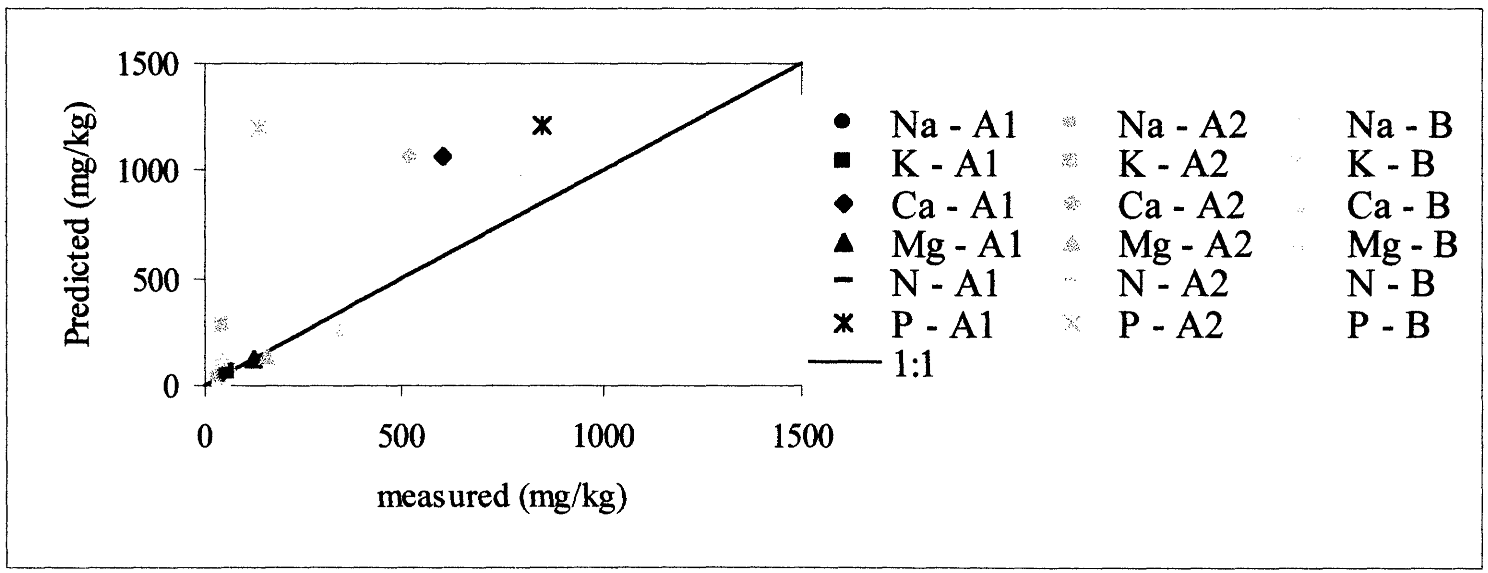


Figure 7.5. Predicted and Measured Values for 4Mar97

7.2.2 Comparison of Simulated and Measured Crop Uptake

Crop uptake is one of the three pathways for the nutrients removed from the system and the simulated versus measured values for each of the nutrient taken up by the crop are shown in Figure 7.6. The model underestimates the uptake of N and K, with the simulated K uptake being a little less than half the measured uptake. The underestimation of N and K uptake is a function of these elements being depleted in the soil solution at periods of rapid crop growth simulated in the EMU model. From the point of view of assessing the environmental impacts of the utilisation of manure and effluent, it is preferable that the model underestimates crop uptake, rather than overestimates. In the current version of the EMU model, nutrient deficiencies do not limit crop growth, which should be included in further developments of the model.

As stated previously it is difficult to verify the total quantity of nutrients lost in drainage. Application of conservation of mass principles indicates that the modelled drainage losses are satisfactory, as the simulated soil values, runoff losses and crop uptakes are within in the same order of magnitude of the measured values.

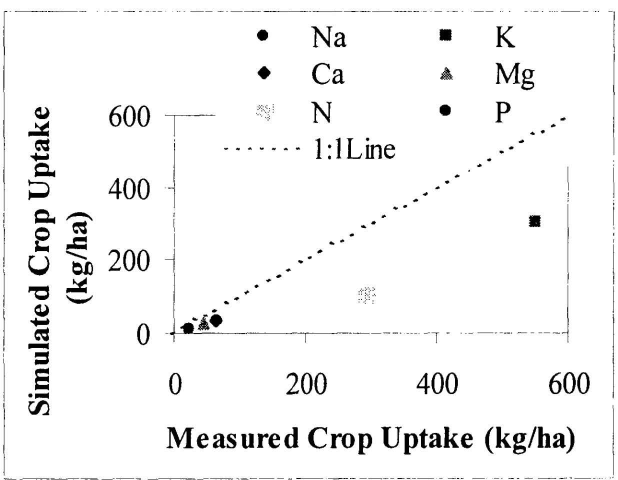


Figure 7.6. Simulated Crop Uptake Versus Measured Crop Uptake for Simulated Nutrients

7.2.3 Test of Random Number Generator

The random number function (Rnd) in Access is used as the basis for generating rainfall, evaporation and the characteristics of the other stochastic inputs to the model. To test that the random number does sample from a uniform distribution, over 13000 numbers were generated and a histogram of these data is shown in Figure 7.7. This figure indicates the uniform distribution of the random numbers generated by the "Rnd" function in Access is satisfactory.

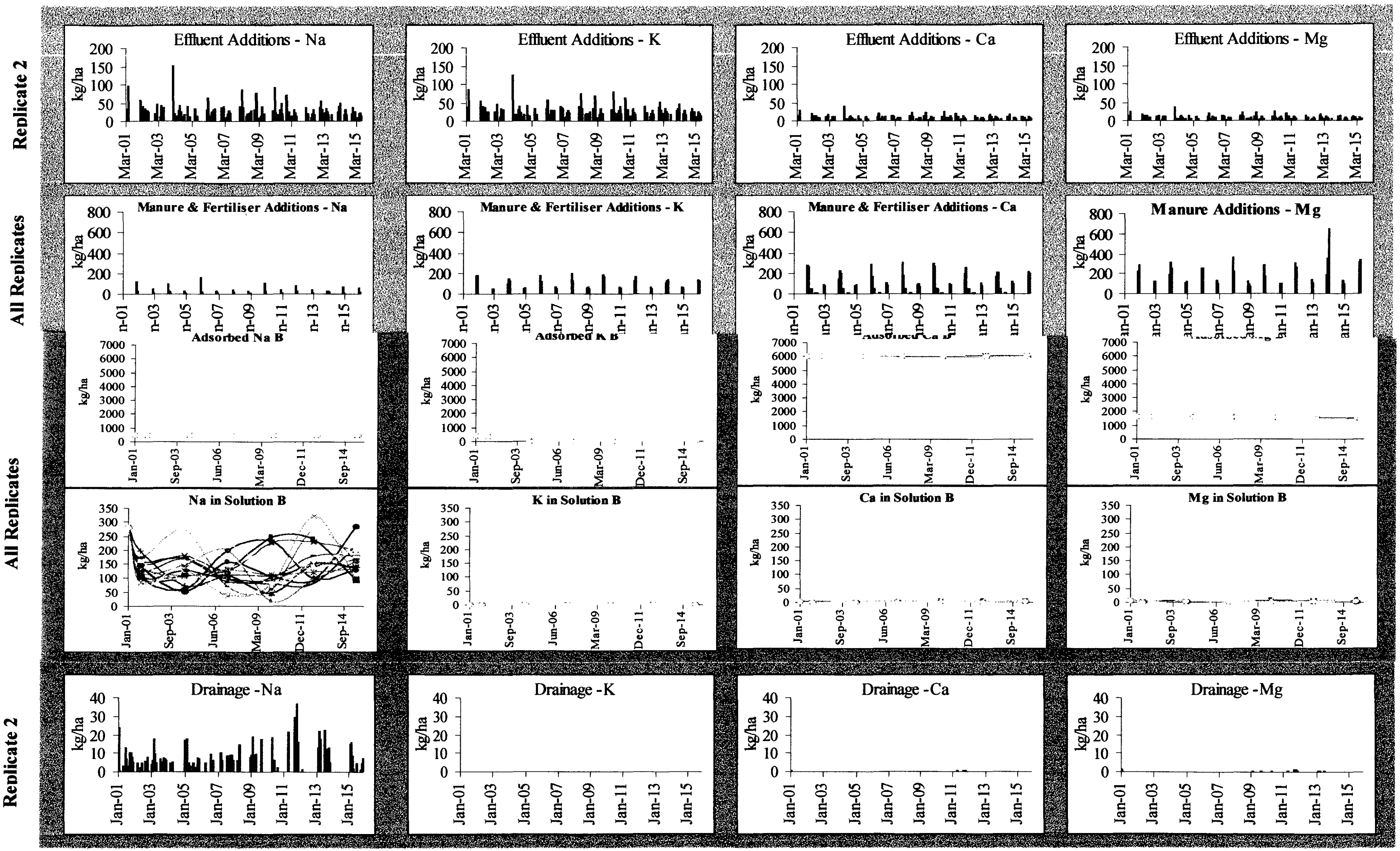


Figure 8.1. 15 Year Simulation at "Tullimba" Feedlot – 20 Replicates

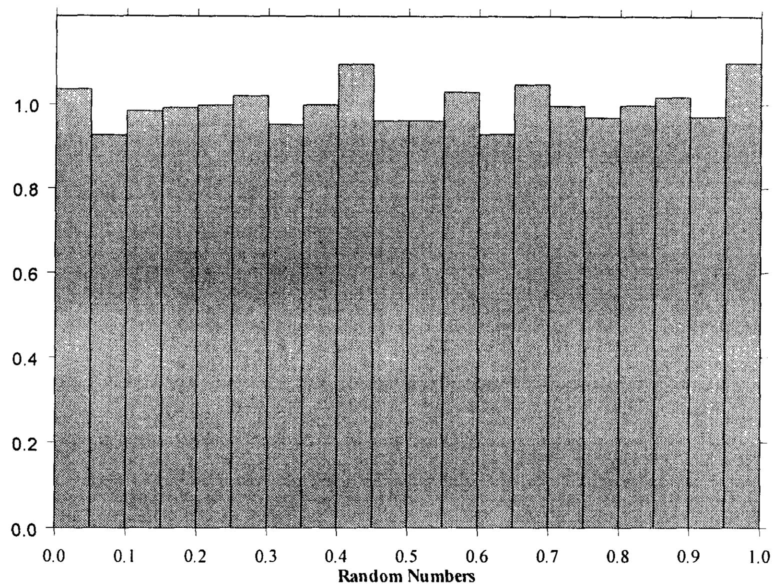


Figure 7.7. Histogram of 13140 Random Numbers Generated by the Access function Rnd

7.3 Check of Model Mass Balance

The EMU model does not have an analytical solution that can be used to validate the outputs but uses a simple mass balance for each nutrient (Equation 7.3) to check the model calculations. The results, as indicated in Table 7.2, suggest that the calculations carried out by the model are valid in the context of a simple mass balance.

Initial Store + Inputs – Outputs – Final Store = 0 .... **Equation 7.3**

Table 7.2. Check of Model Output using a Mass Balance of each Nutrient

Nutrient	Initial Soil Store (kg/ha)	Inputs		Outputs			Final Soil Store (kg/ha)	Initial + Inputs – Outputs – Final
		Manure (kg/ha)	Effluent (kg/ha)	Crop (kg/ha)	Drainage (kg/ha)	Runoff (kg/ha)		
Na	745	136	4180	260	3723	92.7	985	-2.39E-12
K	1910	855	4149	5443	187	70.1	1213	-1.66E-11
Ca	12272	1587	1519	573	2703	58.9	12043	-8.55E-11
Mg	2323	2087	1412	405	1533	22.6	3861	-1.96E-11
N	13551	2670	165	2278	235	5.8	13867	5.38E-10
P	9802	790	659	0	0	10640	612	1.51E-11

7.4 Sensitivity Analyses

Sensitivity analyses are carried out using the actual rainfall and evaporation data as input over a 3.5 year period. The only two parameters in the model for which a value cannot be estimated from collected data are the coefficient in the crop growth model (mu), and the crop dry weight for 90% light interception (w90) (see Sections 5.7.11 and 5.7.12) (Johnson 1998). Therefore, these two constants are used in a sensitivity analyses because of the uncertainty of the value they should be assigned (Millard 1998). "mu" is a constant that can take on the value between 0 and 1 and has the effect of extending or compressing the sigmoidal crop growth curve. The modelled evapotranspiration processes are a function of ground cover, which in turn is a function of crop weight and "w90". The value that "w90" can take on also varies between 0 and 1, and sensitivity analyses are carried out by incrementing each of these values by 0.2, with three replicates for each value.

Analyses of variance tests are applied to the output data to determine if there is any significant difference in the output when changing "mu" and "w90" over their range of values. The ANOVA test relies on the assumption of a normal data distribution and for data that does not fit the normal or lognormal distribution, a Kruskal-Wallis Rank Sum test is used. The analyses of variance tests indicate that there is only a significant difference ($p<0.05$) for the amount of inorganic N and K lost in runoff across the range of values of "mu" (see Appendix F to Appendix K). "w90" has no effect at all on the runoff of any of the nutrients over the range of values tested. Total inorganic N lost in drainage is the only nutrient for which there is a significant difference for the range of values of "w90" and "mu" ($p<0.05$).

For crop uptake all the nutrients, except N as a function of "mu", have significantly different means ($p<0.05$). This is a result of the crop deficiency that occurs for this nutrient, and not for other nutrients. Increasing "w90" and "mu", has the effect of decreasing the crop uptake of each nutrient and this is shown for "w90" in Figure 7.8 and "mu" in Figure 7.9. The difference in the means for nutrient uptake as a function of "mu" is only evident for the higher values of "mu". Figure 7.8 and Figure 7.9 also indicate that the N deficiency experienced by the crop increases the variation in the modelling results.

The lack of sensitivity observed for most of the range of values of "mu" and "w90" suggest that an average value will be satisfactory for use in the model. Therefore, the model will be used with "mu"=0.5 and "w90"= 0.5.

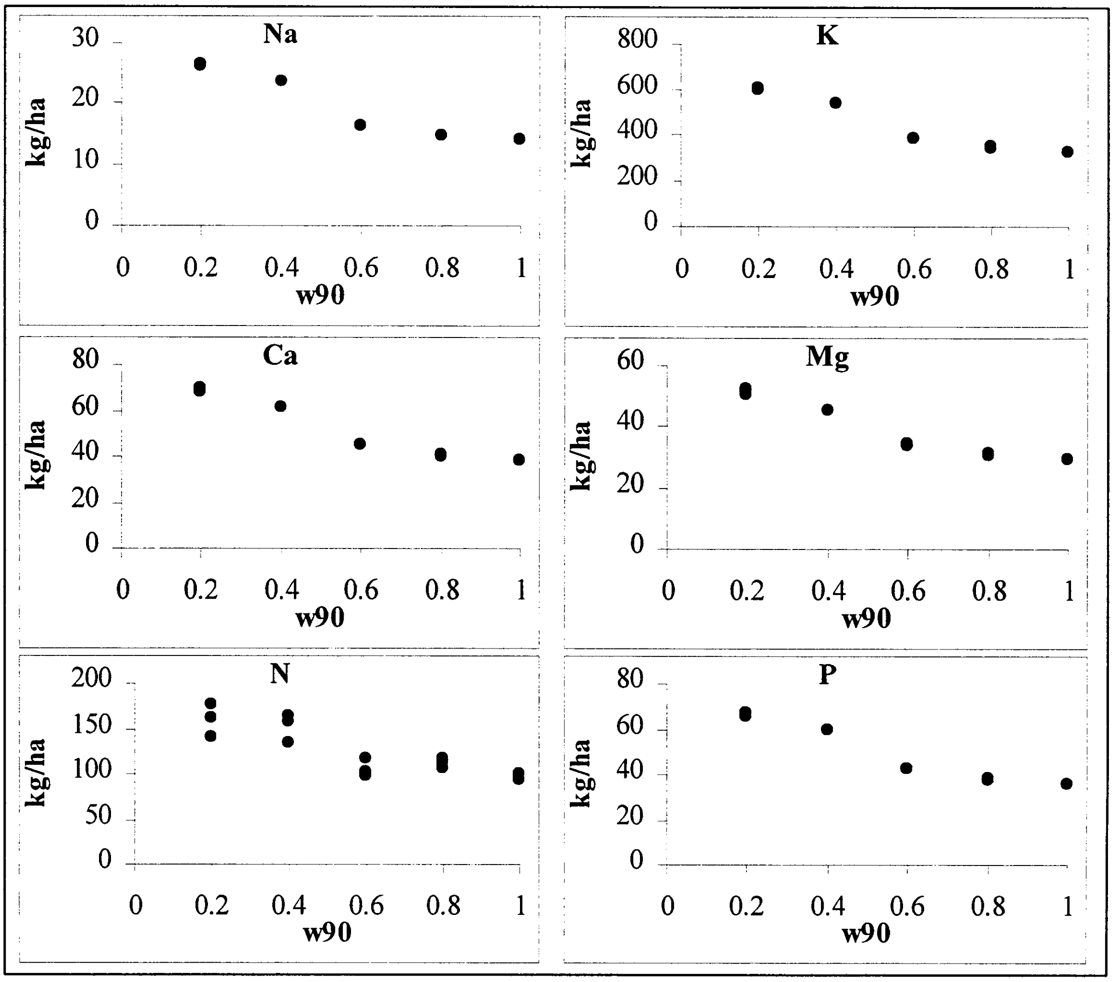


Figure 7.8. Crop Uptake as a Function of "w90"

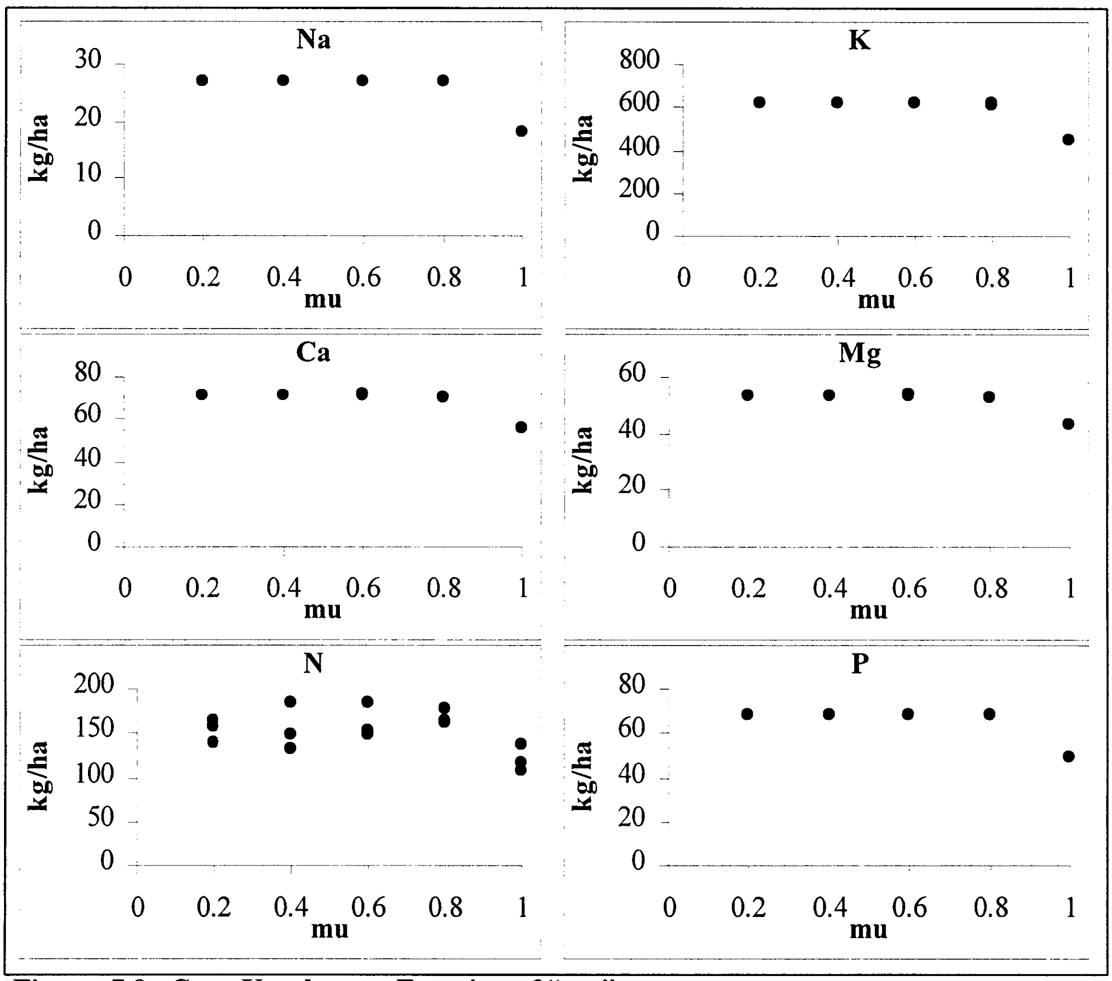


Figure 7.9. Crop Uptake as a Function of “mu”

Chapter 8. Modelling the Tullimba Irrigation Area

Two investigations using the EMU model are used for the purpose of this study. The first investigates the sustainability of the Tullimba irrigation area through a fifteen year simulation of the cropping, manure and fertiliser regimes (Appendix L) practiced over the last 3.5 years. The second use of the EMU model compares current practices with manure application at various rates over a simulated six year period.

Output data from all the simulations are used to investigate the behaviour of the manure and effluent utilisation system in a variety of ways. Total monthly losses via drainage and runoff are presented in the form of probability functions for the gross amount of each nutrient leaving the irrigation area, in any month. Also presented are average concentration data for each of the nutrients in runoff and drainage for each month.

8.1 Fifteen Year Simulation of Tullimba Irrigation Area

Simulating the feedlot system over varying time horizons must be considered with some caution. Predicting the sustainability of a manure and effluent utilisation system beyond a period when factors that influence the systems sustainability are likely to be considerably different to the present conditions could be misleading. The changing factors that influence the sustainability of an agricultural system are the prevailing climate, management practices and technological advances. A fifteen year period was used for this simulation because attempting to include the possible changes in these factors beyond such a time period would add another level of complexity to the modelling process. Having the model in the Access environment will make it a lot easier to include these changing factors and the model should be used whenever conditions change so that the effects of these changes can be readily observed.

An important component of the modelling exercise is determining the cropping cycle and the timing of effluent applications. The aim of the model is to investigate the utilisation of the nutrients in the manure and effluent, and the application times and amounts and the crop cycle are based on current practices. Application of effluent for all the simulations is based on soil moisture, with a refill point halfway between wilting point and field capacity for each soil layer. The cycle of crops, manure and fertiliser application over the past 3.5 years is repeated 5 times over the 15 year simulation with twenty replications. Twenty replications are used to characterise the variability of the system.

8.1.1 Simulation Output

Figure 8.1 shows the time series of all cation pathways modelled over the fifteen years and Figure 8.2 summarises these data. Some of the graphs in Figure 8.1 include data from all replicates, while others graph only replicate 2 from each simulation. Total cations lost through drainage, leachate, runoff, and crop uptake or added to the system through manure and effluent additions is visually represented in Figure 8.2.

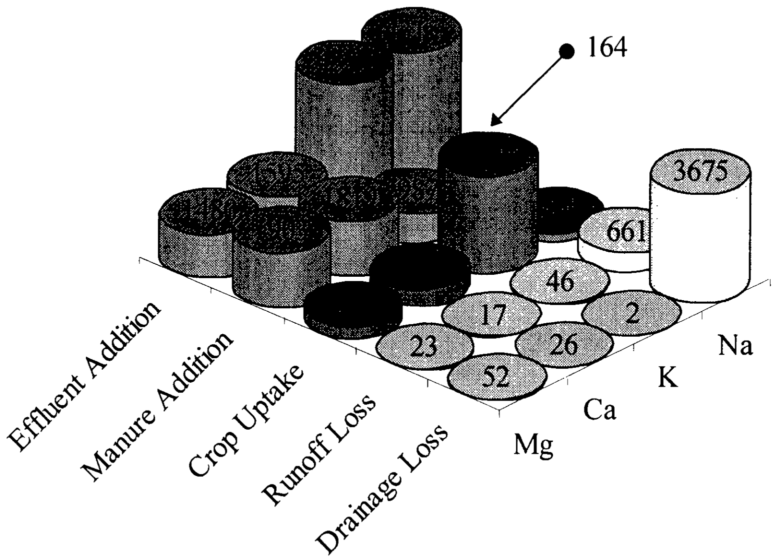


Figure 8.2. Gross Amount of Inputs and Outputs (kg/ha) over 15 Year Simulation

The time series of the cations adsorbed and in solution in each layer, presented in Figure 8.1 were constructed by sampling the modelling results every 1000 days. The time taken to run the query that was built to sample all the replicates for all of the cations is a function of the sampling interval and the shorter the interval the longer the query takes. Therefore, an interval of 1000 days was chosen, however, as will be shown later, this interval is quite unsatisfactory.

Effluent additions for the four cations (Na, K, Ca and Mg) are shown in the first row of graphs in Figure 8.1. These graphs indicate the relative cations added in the effluent, with the Ca and Mg additions in the effluent being of similar magnitude to each other but less than the additions of Na and K. Conversely, the additions of Ca and Mg in the manure are greater than the amounts of Na and K added in the manure (second row of graphs in Figure 8.1). Ca additions occur more frequently, as there are regular applications of super phosphate, which contains 20% Ca. Applications of super phosphate have in the past been at the rate of 250 kg/ha in January and 60 kg/ha in May every second year, and this same cycle was included in the simulation. Relatively the same amount of each cation is being added in the combined manure and effluent and over the 15 years simulated, approximately 4.5t of Na, 5.3t of K, 3.4t of Ca and Mg are added to the system (Figure 8.2).

The relative amount of each cation lost through runoff is shown in the third row of graphs in Figure 8.1. This highlights that considerably more Na is lost via this pathway than the other three cations. The last row of graphs in Figure 8.1 indicates the same pattern for the drainage pathway. In contrast to this, the fourth row of graphs indicates that the crop takes up 8-10 more times K than the other three cations.

The effect of these imbalances in additions and uptake are shown in the fifth to tenth rows of graphs in Figure 8.1 for the A1, A2 and B soil horizons. Graphs in rows 5 and 6 plot the time series of the four cations in the adsorbed state and in solution for the A1 horizon. These graphs indicate that increases of K, Ca and Mg follow a linear trend, with the increase in K being slightly greater than Mg or Ca and in proportion to the greater amount of K added in the effluent and manure.

Graphs in rows 7 and 9 indicate the behaviour of the adsorbed forms of the cations in the A2 and B horizon, respectively. The amount of Na and Mg adsorbed in the A2 and B horizons remains relatively constant while there is a small decrease in the large amount of Ca adsorbed. In contrast, K is completely depleted in the A2 horizon by the seventh year and in the B horizon by the fourth year, as a result of crop uptake.

A sinusoidal pattern that is associated with the cations in solution for all horizons is indicated in Figure 8.1. This pattern is similar for each replicate in the A1 and A2 horizons and more random for the B horizon. The amount of nutrient added to the A1 horizon is dependent on the amount in the irrigation and also the amount lost in runoff. Irrigation fills each horizon to field capacity and if rain occurs during the following days, there will be some redistribution of the water and nutrients through the profile. The greater variation in the A2 and B horizons is likely to be a function of the amount of rainfall that occurs in the days subsequent to an irrigation event.

The crest of the sinusoidal wave for the cations in solution in the A1 horizon, shown in Figure 8.1 (graph row 6), is greater for the Na concentrations, but the pattern is also evident in the other cations at a smaller scale. The graphs indicate this pattern spans a 7 to 8 year period, however there appears to be no reason why this should be the case. These graphs were constructed by sampling the model output approximately every three years and when the daily model output is used to construct the graph a very different pattern emerges, shown in Figure 8.3 for Na in solution in each horizon.

Figure 8.3 shows the Na added in the manure and irrigation applications over the same time horizon as the time series of Na in solution in the A1, A2 and B soil horizons and the losses of Na in the leachate. These graphs indicate that the Na in solution within the A1 horizon is associated with the irrigation season. The Na levels fluctuate around a mean value that is dependent on the initial concentrations, as the exchange constants are based on these initial concentrations.

There are accumulations of Na in the A2 and B horizons, however the average Na in solution in the A1 horizon remains relatively constant. Generally there is an accumulation of Na in the A2 and B horizons, while the levels in the A1 horizon fluctuate around an apparently stationary mean. Leaching events reduce the Na in solution in the A2 and B horizons, therefore the concentration of Na in solution in these horizons is a function of significant rainfall events.

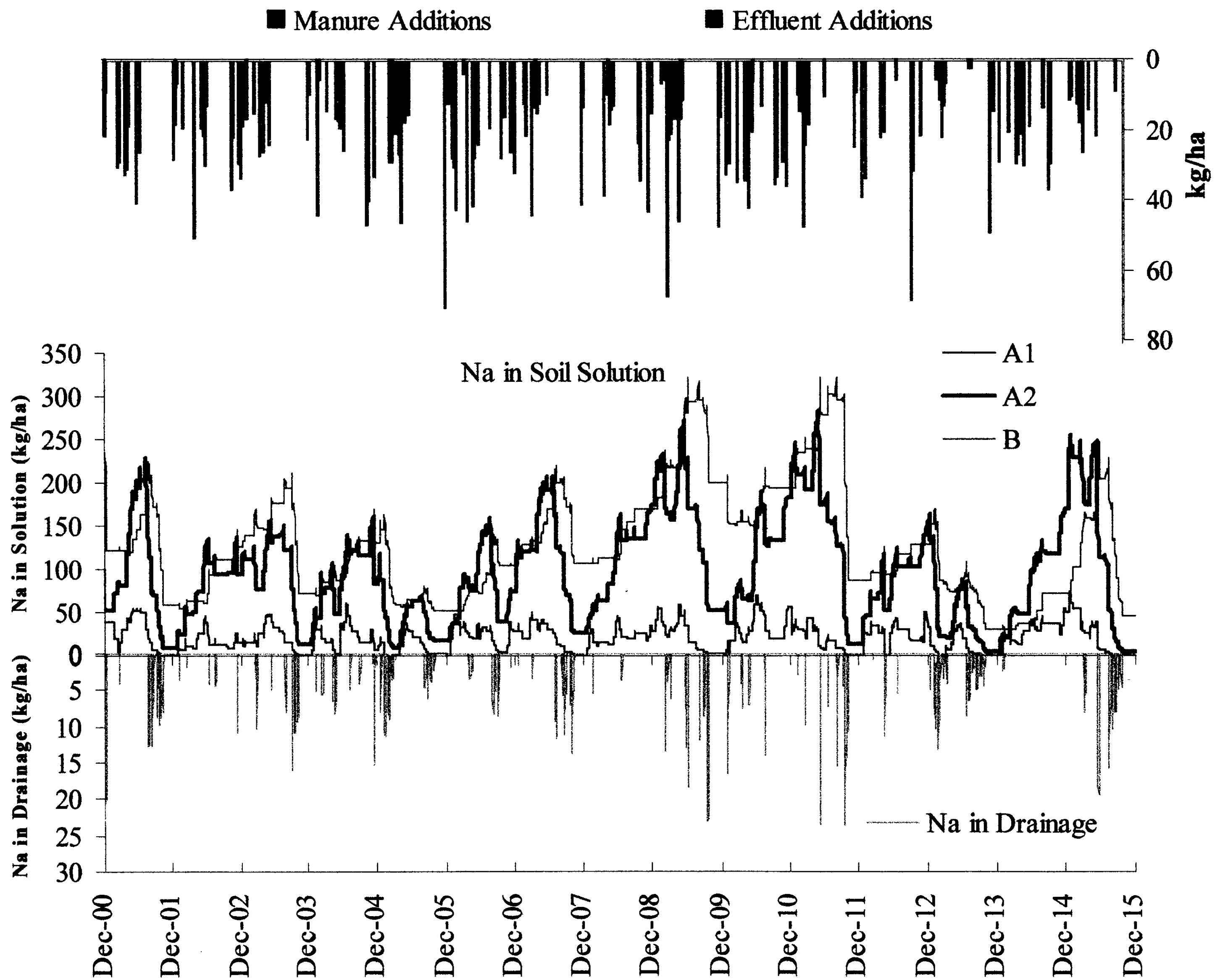


Figure 8.3. Time Series of Na in Solution in Soil Profile with Na Additions in Manure and Effluent and Losses in Drainage

Cation exchange and climatic cycles were the only processes modelled that affect the behaviour of the cations in solution in the soil profile. Further investigation of the processes modelled and the model output is required to clarify which of these has the most effect within each soil layer. When effluent is added to soil, the majority of K, Ca and Mg in the effluent are exchanged to the adsorbed form. The amount exchanged is dependent on the concentration of each cation in the absorbed form and in solution, and the balance of cations. The reverse is true for Na and depending on the relative amounts of each cation present in solution, the addition of Na in the effluent can cause more to be released from the adsorbed form to Na in solution.

The cation exchange capacity (CEC) in the top layer is increased with each manure application. The modelled behaviour of the CEC, shown in Figure 8.4, indicates the variability in the CEC measurements but also shows an increasing CEC from the addition of the manure. This graph was constructed by sampling the amount of each cation adsorbed and in solution every 100 days from replicate 1. These were than converted to mequiv/100gms and the calculated CEC is the total of the four cations both adsorbed and in solution.

The CEC graph (Figure 8.4) indicates the linear increase of the CEC in the A1 horizon. Comparison with the steady increase in the adsorbed K, Ca and Mg in the A1 horizon (Figure 8.1) suggests that the increase in CEC is a result of the manure additions. There is greater variation in the CEC of the A2 horizon than in the B horizon, which is partly a result of the greater losses of K, Ca and to a lesser extent Mg from the A2 horizon than from the B horizon.

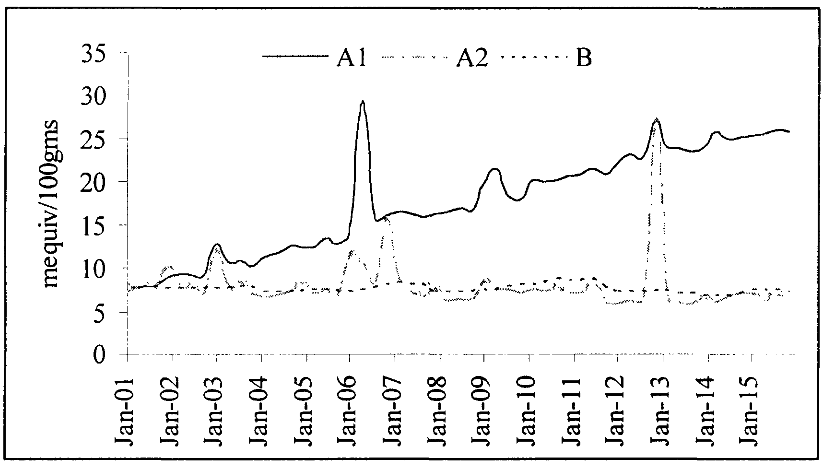


Figure 8.4. Time Series of Cation Exchange Capacity of the Soil Profile

Another factor that effects the CEC calculation is the soil moisture in each horizon. CEC is a function of the sum of the cations in the adsorbed form and in solution in units of mequiv/100gms. The adsorbed form is converted to mequiv/100gms through calculation of the depth and density of the soil, while the mequiv/100gm of cations in solution is a function of the depth of soil water, with the density of the soil water assumed to be 1. Therefore, soil moisture has a big effect on the variation of the CEC in the EMU model and as less water is removed from the deeper soil horizons by evaporation, the variation of the CEC decreases with depth.

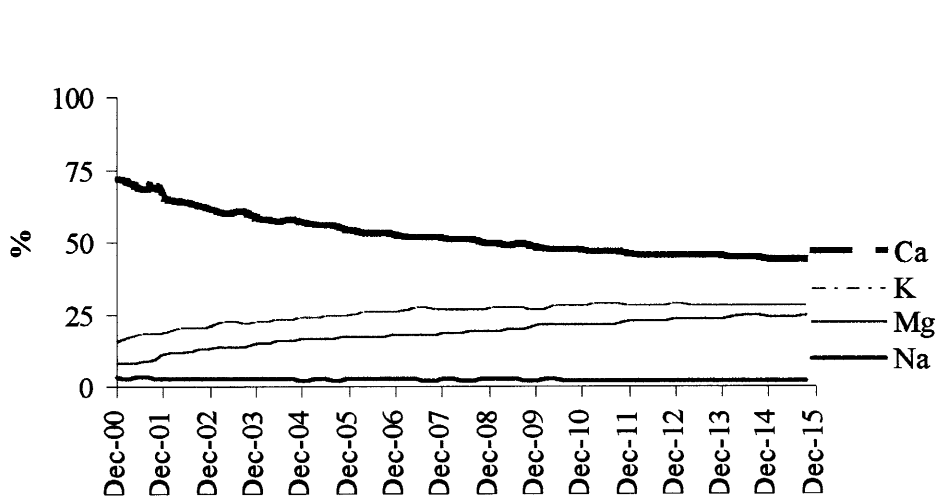
During periods of rapid crop growth, irrigations can occur at frequent intervals. When the soil moisture reaches the refill point the soil moisture in the A1 horizon is incremented by the amount required to fill the soil profile to field capacity. Any runoff that occurs as a result of the addition of the effluent, extracts some of the nutrient. However, runoff should only occur if a rainfall event occurs shortly after irrigation. There is likely to be drainage to the A2 and B horizons and therefore, the variation of soil moisture, and hence nutrients in solution, in the A2 and B horizons are governed by the drainage characteristics as well as the antecedent moisture conditions within each layer. Irrigation application rates should be such that no deep drainage occurs unless there is rainfall subsequent to the irrigation event. If this occurs, there may be some nutrient lost out of the B horizon.

A time series of the major cations in each soil horizon is shown in Figure 8.5, to indicate the relative percentage changes that occur through the soil profile for the 15 year simulation. The changes are mostly attributed to changes in the adsorbed form of the cation as those in solution tend to fluctuate around a mean value (see Figure 8.1). There is a 25% decrease in the relative amount of Ca in the soil and approximately a 15% increase in the relative amount of Mg in the soil over the 15 years simulated. During this time the relative amount of Na remains relatively constant and the increases in K are very similar to the increases in Mg.

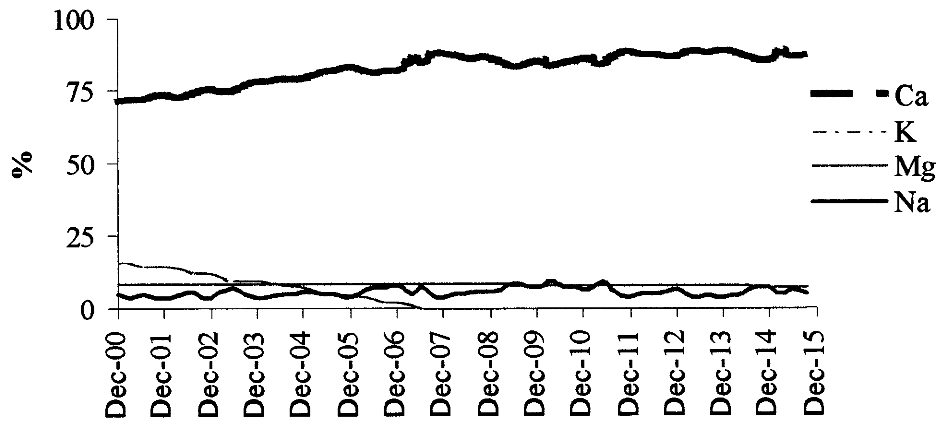
An increase in the percentage of Mg and a decrease in the percentage of Ca have important implications for the structural stability of clay aggregates (Figure 8.5). These changes may cause the clay aggregates to swell and become more easily dispersed (Leeper & Uren 1993), which is particularly important for the sodic subsoils of the Tullimba irrigation area. However, as indicated in Figure 8.5, the simulation only predicts these changes to occur in the top horizon and it also appears that a new equilibrium is reached after approximately 11 years of continuous manure application. This is a function of modelling the cation exchange using the Gapon exchange equations (Frissel & Reiniger 1974) and until there is data to verify this process caution is required when interpreting the model output.

In the A2 horizon the only changes are a small increase in total Ca and the complete depletion of K (Figure 8.5). In the B horizon the percentage of all total cations remain static, with the exception of K, which is completely depleted. It is unexpected that the relative percentage of Na in each horizon would remain fairly constant, indicating that most of the additions are subsequently leached through the profile.

Relative Soil Cation Percentages – A1 Horizon



Relative Soil Cation Percentages – A2 Horizon



Relative Soil Cation Percentages – B Horizon

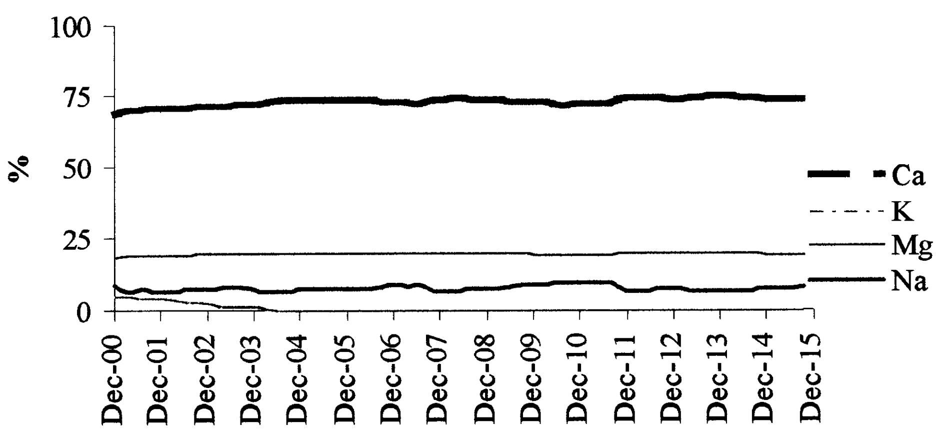


Figure 8.5. Time Series of Relative Cation Percentages in Each Soil Horizon

The modelled inorganic N in the soil solution sampled every 1000 days displays a similar pattern to the cations in solution sampled using the same time interval. The 20 replicates for the 15-year simulation, shown in Figure 8.6, indicate that in the A1 and A2 horizons, when the Na levels rise the N levels appear to diminish. Within the A1 horizon, the levels of inorganic N and Na in solution follow a similar pattern for each replicate, whereas for the A2 horizon, the pattern remains similar for inorganic N with more variation between replicates evident for Na in solution. In the B horizon the inorganic N is again uniform between replicates but there is a lot of variation between replicates for Na in solution.

The only difference in the processes modelled for Na and inorganic N in solution is the cation exchange for the Na and the mineralisation of organic N to inorganic N. The variation evident in Figure 8.6 for Na in the B horizon is therefore a function of these differences. The majority of the organic N is added to the A1 soil layer through manure additions. This is then mineralised to inorganic N by daily mineralisation and this inorganic N moves through the profile with the changing soil moisture. However, the majority of the Na is added in the effluent along with varying amounts of the other cations. The modelled cation exchange processes then redistributes the amount of each cation on the exchange complex and in solution. As the soil moisture redistributes these cations throughout the different soil layers, the cation exchange process again redistributes the cations between the adsorbed form and those in solution. This has a compounding effect on the levels of the cations in solution and in the adsorbed form and introduces a greater variation between the replicates in the B horizon.

The observed patterns in Figure 8.6 is known as aliasing and highlights the problems of sampling a periodic signal at a frequency less than the dominant frequency present in the signal (Smith, R. 1999, pers. comm., 6 Sep). An investigation of the phenomenon is outside the scope of this thesis, but the previous discussion is included to highlight the importance of selecting a sampling frequency that reflects the true characteristics of the system.

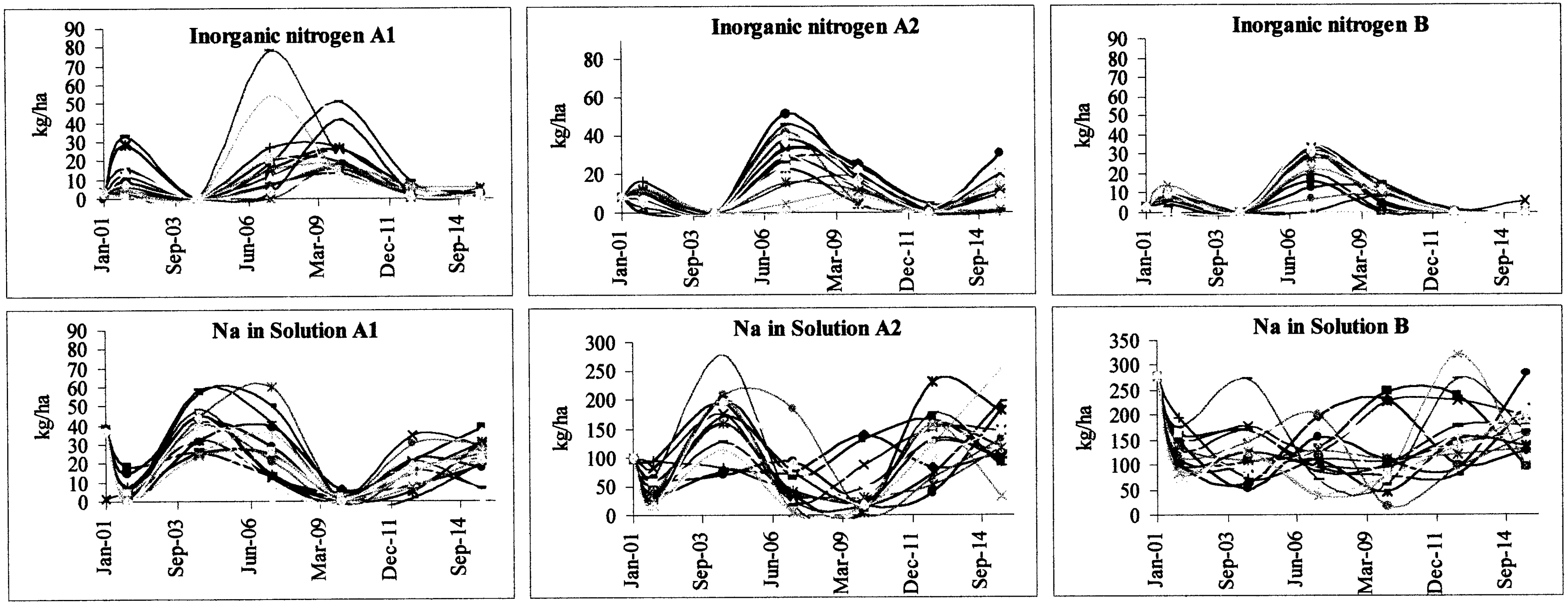


Figure 8.6. Comparison of Inorganic N and Na in solution in Each Soil Horizon for 15 Year Simulation - 20 Replicates

Sampling the model output daily produces a different pattern compared with the 1000 day sampling interval, as shown for 1 replicate for N additions and inorganic N in the A1 Horizon in Figure 8.7. The inorganic N increases coincide with the addition of manure and these affects are more noticeable than for Na (see Figure 8.3), because the N additions in the manure are of an approximate order of magnitude greater than the Na additions in manure. Conversely for the effluent additions, there is 75 times the amount of Na added compared to inorganic N. This factor increases to approximately 1060 for organic N.

The N additions in the manure are considered to be in the organic form and the fertiliser additions in inorganic form. The spikes in the inorganic N in the soil are associated with the inorganic N fertiliser additions. There are 30 applications of N through inorganic fertiliser over the 15 year period simulated.

The apparent pattern similarities between inorganic N and Na in solutions indicated in Figure 8.6 is misleading and highlights the wrong conclusions that can be drawn when sampling on a long time interval (such as every three years). The decease in N is associated with crop uptake throughout the growing season, and also with some leaching of the N through the profile during the irrigation season. The Na depletion is mainly associated leaching of the Na from the soil profile. As a result, during the irrigation season there is little relationship between these two elements, as shown in Figure 8.8.

Figure 8.8 highlights the different behaviour of the inorganic N and Na in solution in each of the soil layers. In the top two layers, both elements are depleted at regular intervals, with the depletion of inorganic N being more frequent than the depletion of Na, due to crop uptake. In the B horizon, an accumulation of Na occurs until there is a significant drainage event. In contrast to this, inorganic N is frequently depleted in the B horizon, with crop uptake and leaching both contributing.

One of the aims of modelling the utilisation of manure and effluent at the Tullimba feedlot is to predict the sustainability of the system. The model predicts that the cations will reach a new equilibrium within the 15 years simulated; the effect of this on other systems is unknown. Because of this, further investigation that is outside the scope of this study is required to confidently quantify the sustainability of the system based on the results presented so far. However, the remainder of this chapter advances the concept of quantifying the sustainability of the system through the use of probability functions of the outputs from this and other simulations, from the perspective of losses through runoff and drainage.

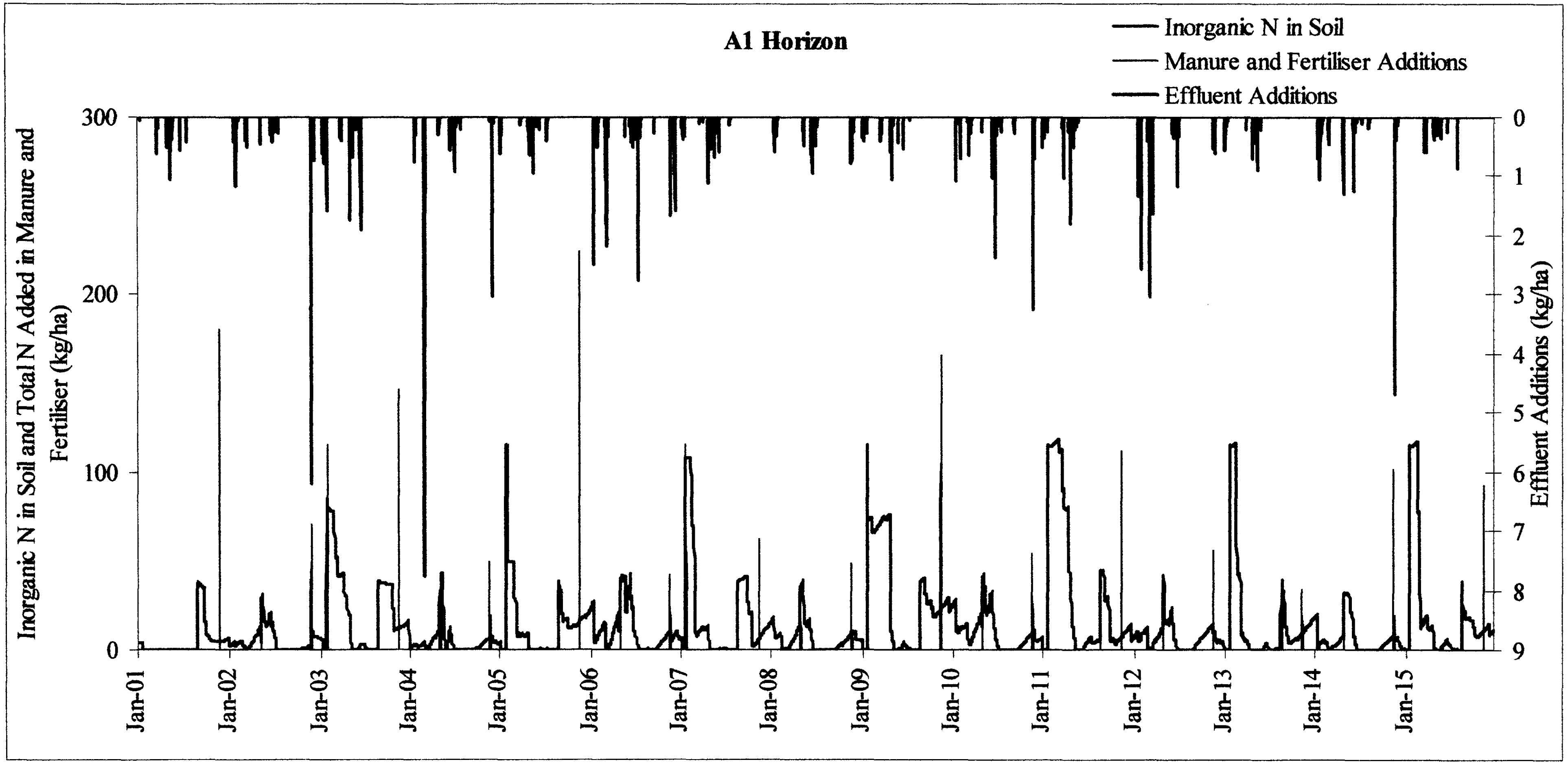


Figure 8.7. Inorganic N in the Soil Solution (A1 Horizon) and Manure and Effluent Additions of Total Nitrogen.

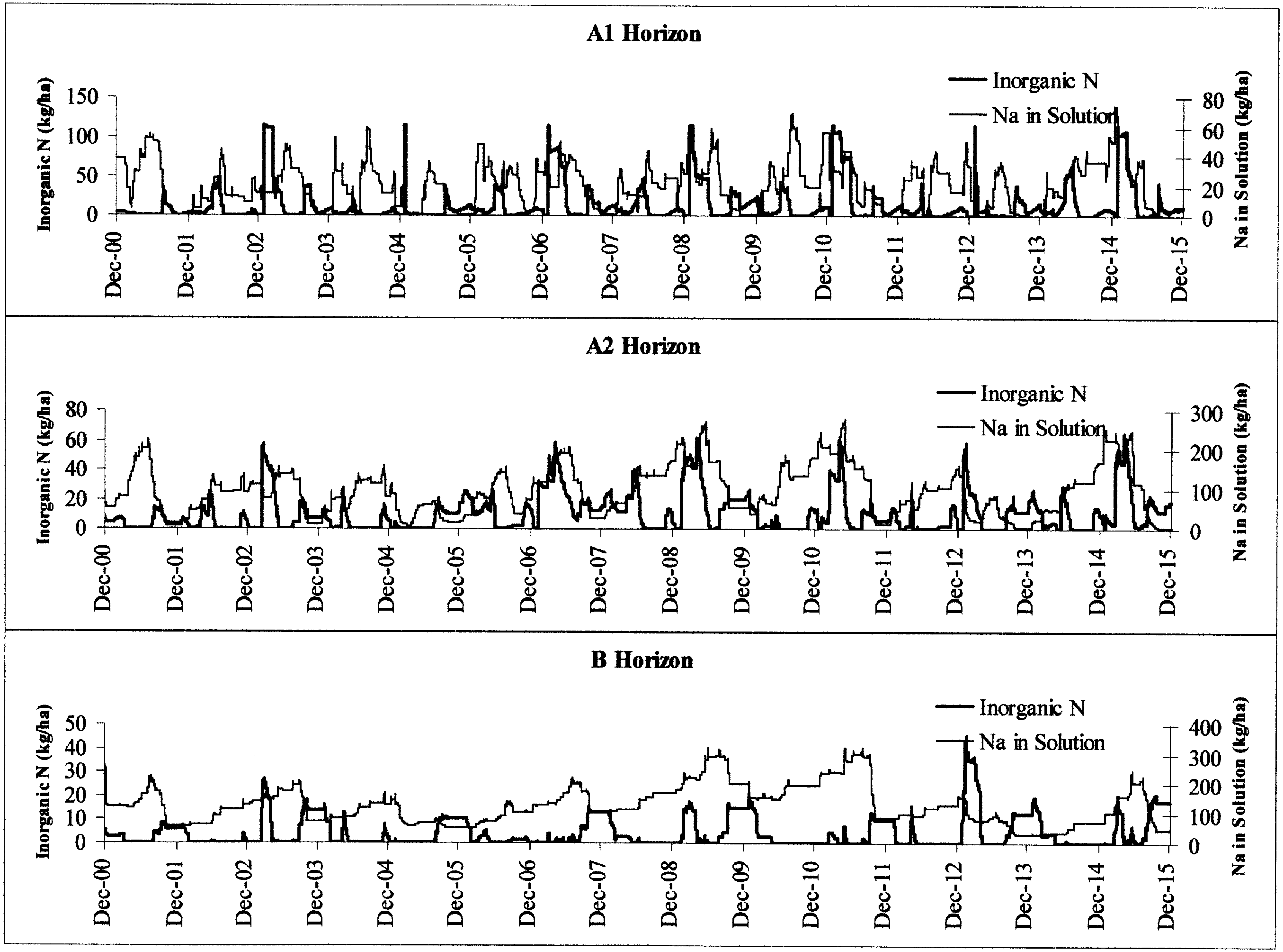


Figure 8.8. Comparison of Inorganic N and Na in Solution for Each Horizon – Constructed by Sampling the Model Output Daily

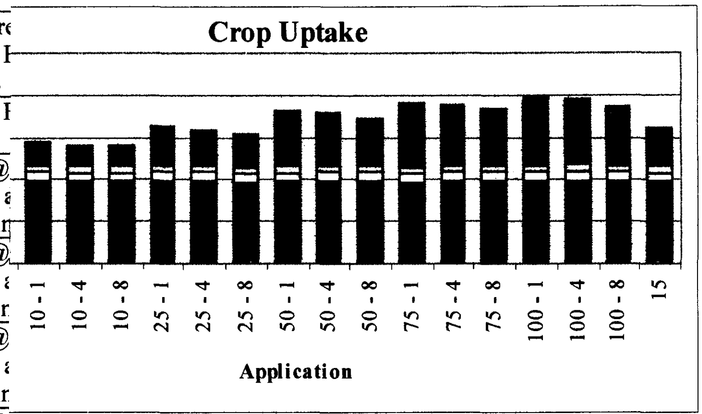
8.2 Six Year Simulations to Study Various Rates and Timing of Manure Applications

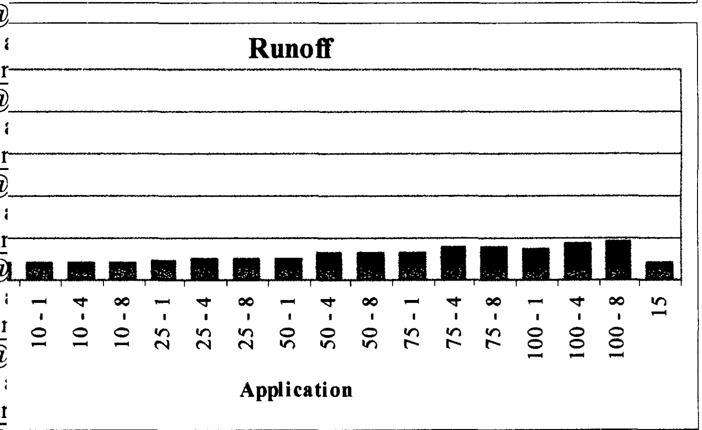
One of the objectives of the EMU model is to investigate various management practices, by running a virtual experiment. To demonstrate the effectiveness of the use of the EMU model in this way, 5 different rates of annual manure applications at three different times of the year were simulated. The rates selected are 10, 25, 50, 75 and 100 tonnes/ha, applied in January, April or August and do not include any inorganic fertiliser additions. Simulations are also run with inorganic fertiliser additions only. Data from the first 6 years of the previously discussed 15-year simulation are used as a treatment with which to compare the different manure application rates.

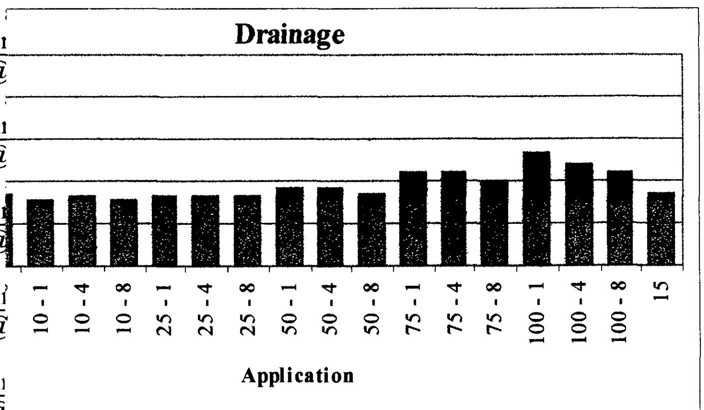
Figure 8.9 graphs the relative amount of the total nutrients added in the manure and/or fertiliser and effluent over a six year period for each treatment. Also included in these graphs are the relative amount of each nutrient that leaves the system through the three output pathways; crop uptake, runoff and drainage. The bottom two graphs in Figure 8.9 combine the manure and/or fertiliser and effluent inputs into one graph and compares this with the total output for each nutrient. The legend for each of the application regimes is included in this figure and this legend will be referred to throughout the chapter in reference to the other figures graphing the output from the EMU model.

Separating the manure and effluent additions in the first two graphs on the left of Figure 8.9 gives a clear picture of the amount of each nutrient added in the different forms. The manure additions include the inorganic fertiliser additions and the graphs to the right hand side in Figure 8.9 indicate that the output pathways for each element are different. This graph also demonstrates the potential for the system to become unbalanced through an accumulation of particular elements in the soil. The totals graphs at the bottom of Figure 8.9 indicate that Na is the only element for which the input approximately equals output for all application regimes. The output of K seems to be relatively constant for all application regimes but the additions of more of this element in the higher manure application rates indicates that there will be some accumulation of this element for these rates.

0 - 0	No Manure Inorganic F Additions
1 - 0	Inorganic F Only
10 - 1	Manure @ tonnes/ha a annually in
10 - 4	Manure @ tonnes/ha a annually in
10 - 8	Manure @ tonnes/ha a annually in
25 - 1	Manure @ tonnes/ha a annually in
25 - 4	Manure @ tonnes/ha a annually in
25 - 8	Manure @ tonnes/ha a annually in
50 - 1	Manure @ tonnes/ha a annually in
50 - 4	Manure @ tonnes/ha a annually in
50 - 8	Manure @ tonnes/ha a annually in
75 - 1	Manure @ tonnes/ha annually in
75 - 4	Manure @ tonnes/ha annually in
75 - 8	Manure @ tonnes/ha annually in
100 - 1	Manure @ tonnes/ha annually in
100 - 4	Manure @ tonnes/ha annually in
100 - 8	Manure @ tonnes/ha annually in
15	First 6 yea year simul







Same as inorganic plus manure applied every tonnes/ha of manure ap years (all applications in

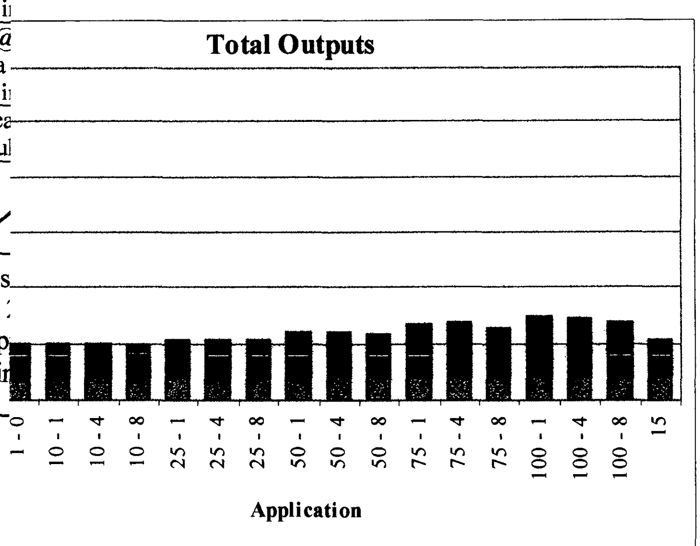


Figure 8.9. Average of (

Graphing each element separately for each total output pathway as a percentage of the total additions, is shown in Figure 8.10. This presentation provides a quick visual indication of the treatments that are causing a build up of each nutrient in the soil and those that are depleting the nutrients in the soil. For example, the total drainage + runoff + crop uptake of Na as a percentage of the additions of Na in manure and effluent remain around the 100% line for the no manure treatment (0-1), the inorganic fertiliser treatment (1-0), the 15/6 tonnes /ha of manure in November + inorganic fertiliser (15), the 10 tonnes/ha of manure applied in January (10-1), April (10-4) and August (10-8) and the 25 tonnes/ha of manure applied in January (25-1), April (25-4) and August (25-8) treatments. For the other treatments, the total percentage reduces for increasing manure application down to approximately 80% for all three application times of 100 tonnes/ha annually. Total percentages of outputs to inputs above the 100% line indicate that overall that particular element has decreased in the soil. This occurs for N and K only for the no manure or fertiliser treatment (0-0) and the inorganic fertiliser only treatment (1-0).

The drainage pathway is the most significant for Na, with the crop uptake pathways being the most significant for N, P and K (Figure 8.10). In relative terms, as the manure application rates increase, there is a greater accumulation of each nutrient in the soil. However, looking at the total outputs can be misleading in terms of what is happening on a time series basis.

Figure 8.10 shows that there is an accumulation of all the elements in the soil for most of the simulations. For N there is an accumulation in the soil at the end of the six years for each application regime, except the no manure application (0-0) and inorganic fertiliser application only (1-0) treatments. However, an investigation of the N deficiencies of each crop, shown Figures 8.11a and 8.11b, indicates there is a N deficiency in at least one crop for every treatment. The graphs in Figures 8.11a and 8.11b also include the N losses in drainage and runoff and are from the same replicate number for each treatment.

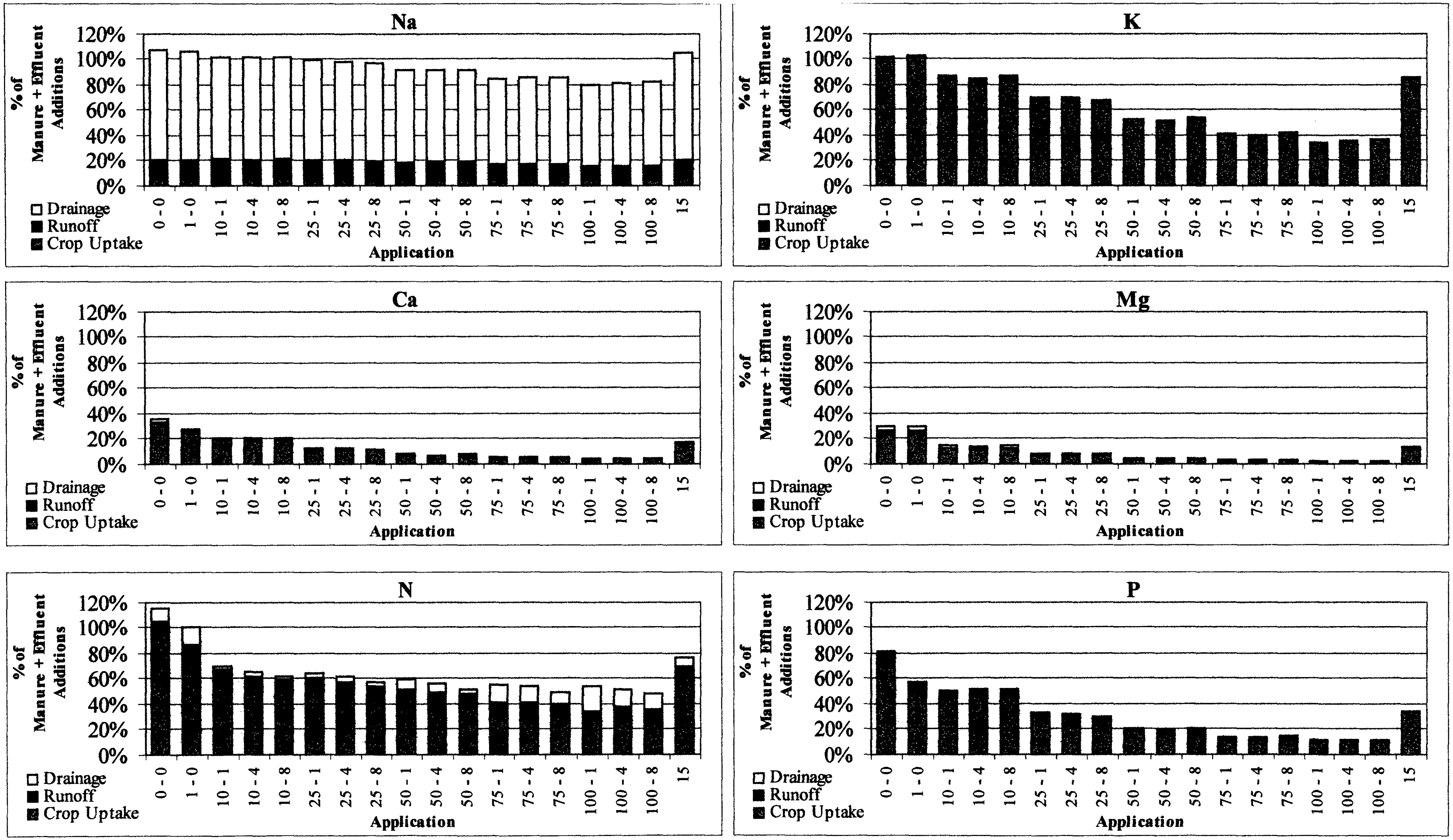


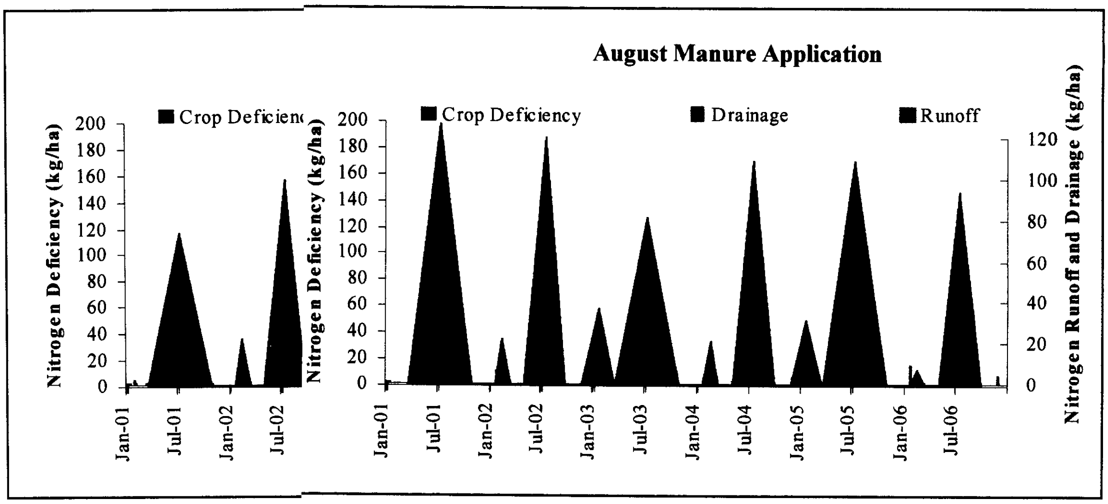
Figure 8.10. 6 Year Total Output Pathways as a Percentage of Total Inputs for Each Nutrient Simulated (Average of 20 Simulations for Each Application - see Figure 8.9 for Application Legend).

Each crop over the 6 year simulations experience some N deficiency for the 10 and 25 tonnes/ha application rates (top two rows of graphs in Figure 8.11a) and the first 6 years of the 15 year simulation plus the inorganic fertiliser and no manure or fertiliser treatments (bottom row of graphs in Figure 8.11b). The third row of graphs in Figure 8.11a indicates that for an annual manure application rate of 50 tonnes/ha, there is some N deficiency in most crops. When 50 tonnes/ha is applied in April, only the last two crops are not N deficient and when applied in August, the second last crop does not experience any N deficiency. However, there is less deficiency in the earlier crops when the manure is applied in January or April. In part, the different amounts of N lost in runoff over the time period graphed for the different application times is a function of the stochastic nature of the EMU model.

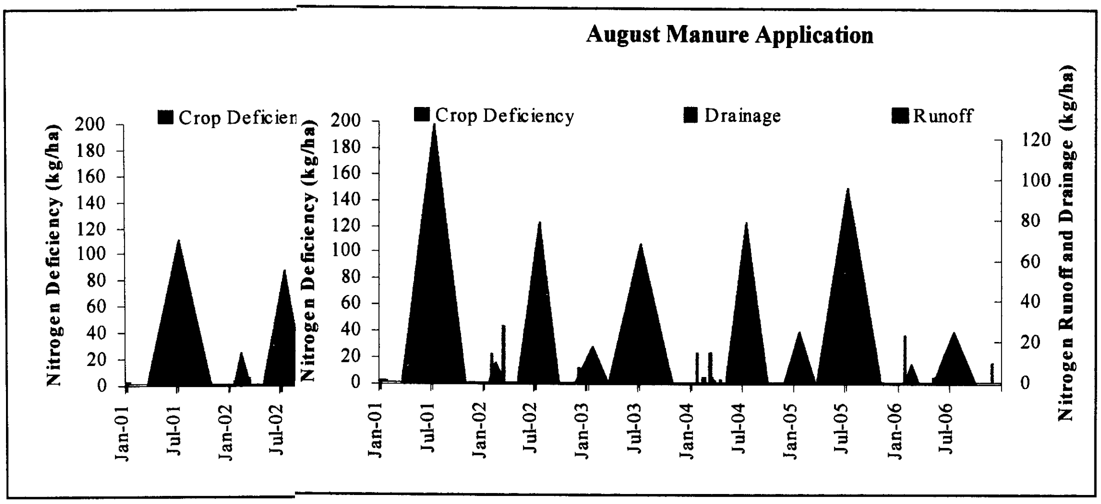
Figure 8.11b graphs the N deficiency for each crop with a time series of N loss through runoff and drainage for the 75 and 100 tonnes/ha application rates in January, April or August, as well as the inorganic and no manure treatments. The first two rows of graphs indicate that applying manure in January or August for both the 75 and 100 tonnes/ha will lead to less N deficiency (except for the first crop which is before the August application), than if the application is made in April. At this stage the EMU model does not account for these deficiencies in the crop growth rate model, but as the graphs in Figure 8.11a and 8.11b indicate, this is a component that should be included in the next version of the model.

Even though the total inputs over the 6 years simulated are greater than the total outputs, the crops do suffer N deficiency and this indicates the necessity to look at not only the total outputs but also the behaviour of the system on a time series basis. To understand the behaviour of the system more fully, a detailed investigation of varies pathways are investigated. The daily model output is used to build a picture of the probability of the amount of each nutrient being removed from the system via runoff and drainage.

10 Tonnes/ha



25 Tonnes/ha



50 Tonnes/ha

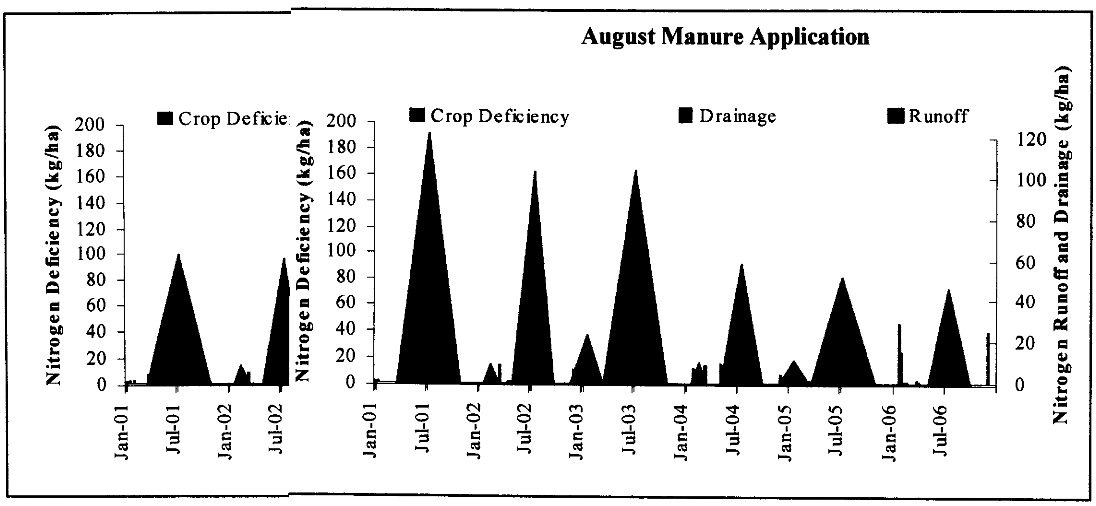
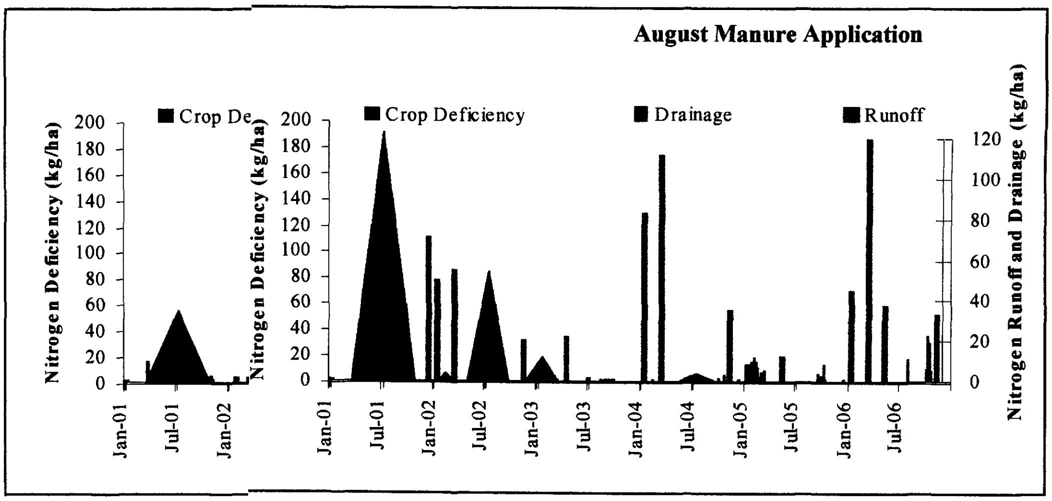
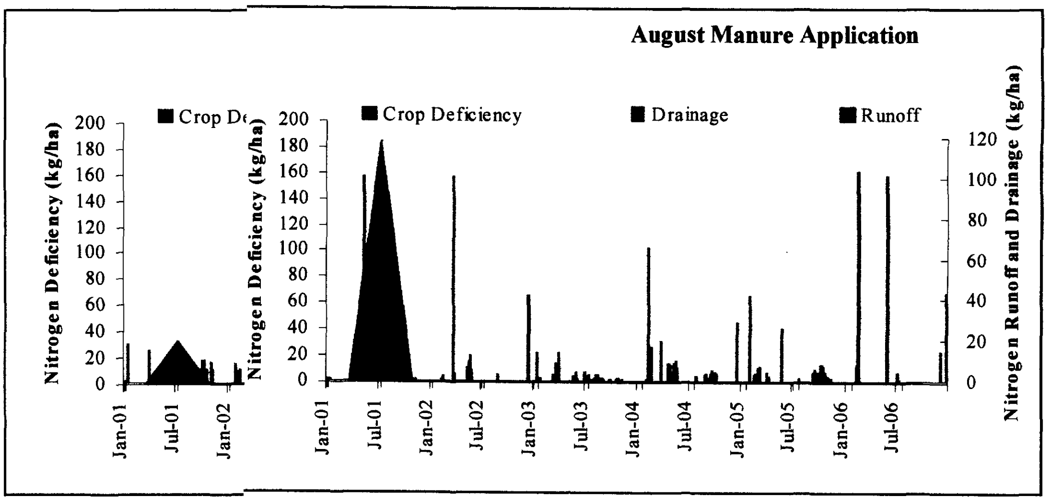


Figure 8.11a. Time Sé and 50 tonnes/ha applied in January, April or August.

75 Tonnes/ha



100 Tonnes/ha



Various Treatments

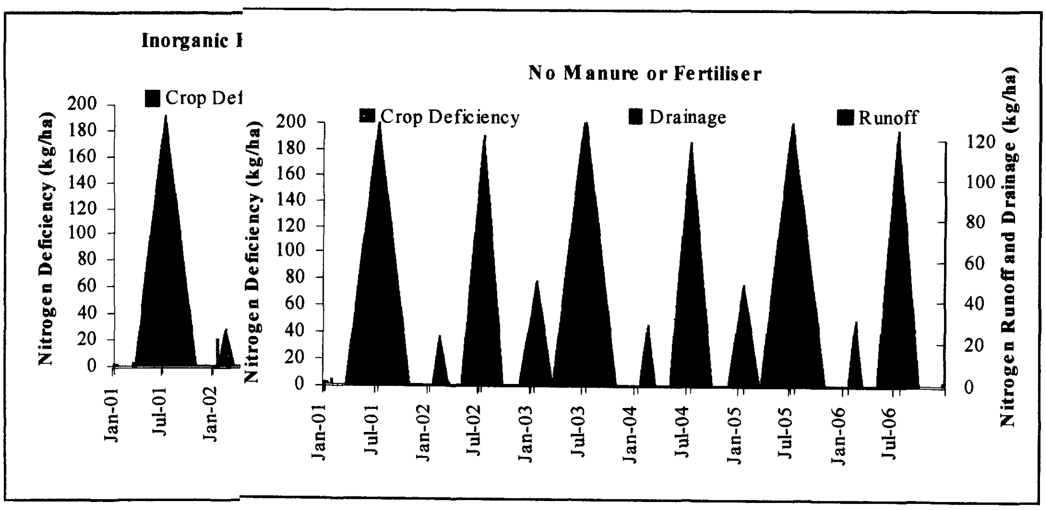


Figure 8.11b. Tim and 100 tonnes/ha applied in January, April or August, Inorganic Fertiliser Only Tr

8.2.1 Runoff

As the model does not include changes to soil structure through the addition of manure, there should be no significant differences in the total amount of runoff across all treatments. Small differences would be expected, given the stochastic nature of the model. Table 8.1 reports the result of an ANOVA applied to the total runoff (mm) over the 6 years (average of 20 replicates for each treatment) and indicates that there is no significant difference between each replicate ($p>0.05$).

Table 8.1. "S-plus" Analysis of Variance Output for Differences in Runoff Totals Over Six Year Simulations (20 replicates for each treatment)

```
*** Analysis of Variance Model ***

           Df Sum of Sq  Mean Sq   F Value     Pr(F)
     month  4     13129 3282.322 0.5976185 0.6645962
      rate  5     26097 5219.394 0.9503047 0.4484973
month:rate  8     13805 1725.654 0.3141930 0.9604954
 Residuals 342  1878379 5492.337
```

While there are no statistically significant differences, an investigation of the depth of average monthly runoff indicates small differences across the treatments (Appendix M). These differences are a function of the stochastic nature of the model and need to be accounted for to accurately determine if the treatments have any affect on the amount of nutrients lost in the runoff for each month. Therefore, to compare treatments, monthly average nutrient concentrations in runoff are used instead of monthly total nutrient losses in runoff.

In contrast to the differences in the average monthly runoff depth between the treatments, there is little difference in the percentage of time (on a monthly basis) that a nominated runoff depth is exceeded, as shown in Figure 8.12. The graphs shown in Figure 8.12 are essentially cumulative density functions, with the y-axis being the percentage of months that a particular runoff depth (x-axis) is exceeded. The only apparent differences are for the 10 and 25 tonnes/ha treatments, indicating the probability of minimal runoff being less for the January application, than for April or August manure applications. This is a result of the stochastic nature of the EMU model and with longer simulations these differences should disappear.

8.2.1.1 Cations

The addition of manure to the top soil layer should reduce the amount of each cation lost in runoff, as there is an increase in the CEC in the top soil layer. This increase in CEC is through the added manure providing more exchange sites. Model output is used to create cumulative density functions, similar to those constructed for runoff depths, and these were used to investigate differences in nutrient losses across the treatments.

The cumulative density function of Na removed in runoff, shown in Figure 8.13, has the same patterns as for the runoff depths and therefore any difference between treatments are a result of the stochastic nature of the model. The probability of less than 0.01 kg/ha/month of Na removed in runoff per month ranges from 0.77 to 0.80 across all treatments and the probability of runoff being greater than 10 kg/ha/month ranges from 0.11 to 0.14. There was no occurrence of Na in runoff exceeding 60 kg/ha/month for any treatment.

Figure 8.14 shows that the behaviour of K in the runoff is similar to Na, with little difference between treatments. The shape of the curves are a little different to the Na probability curves, indicating the smaller probabilities for K in runoff as the amounts increase, when compared with the same amount of Na, which is a function of the greater crop uptake of K. The same "S" curve shape is evident in all the applications, except for the inorganic fertiliser + 15 and 6.5 tonnes/ha of manure applied in November in alternate years. The curve for this treatment indicates a 5% greater probability that more than 1 kg/ha/month of K will be lost from the system than for all the other treatments. This is likely to be a function of the time of manure application for this treatment, as there is no crop to uptake the K added in the manure in any year of the simulation, during most of November (Appendix L).

Figure 8.15 and Figure 8.16 show the probability curves for the amount of Ca and Mg lost in runoff on a monthly basis. The shape of the curves is similar to the K curves, however there are some important differences in the behaviour of some of the treatments. The probability of Ca exceeding 1 kg/ha in any month is 1% to 2% for the no manure, inorganic, inorganic plus manure and the 10 and 25 tonnes/ha rates. However, for the higher rates of application, this reduces to 0.3% for the 100 tonnes/ha manure applied annually in January. Similar trends are observed for the Mg lost in runoff. This is a result of modelling the cation exchange complex and the increased quantities of these two cations held in the adsorbed form in the top horizon as a result of the application of manure. It is expected that the increase would also apply for K, however the crop takes this nutrient up readily and generally it is not available for runoff. Soil physical properties also improve with the addition of manure, increasing infiltration and consequently reducing the depth of runoff (Leeper & Uren 1993). However, this is not included in the model and the trend that is observed with the current algorithms is likely to be enhanced if the runoff module included soil structure as a factor.

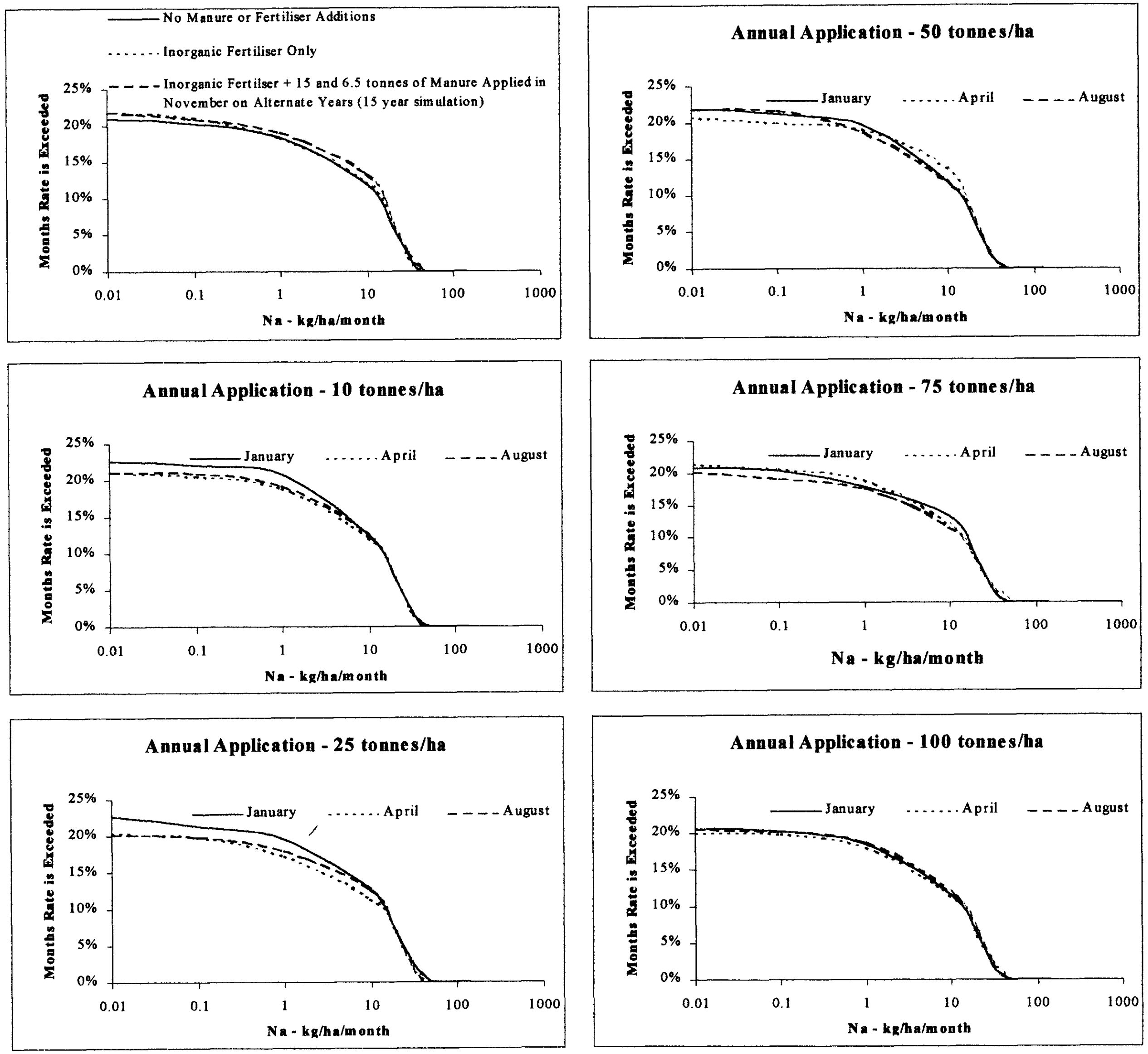


Figure 8.13. Cumulative Density Function of Na Removed in Runoff per Month

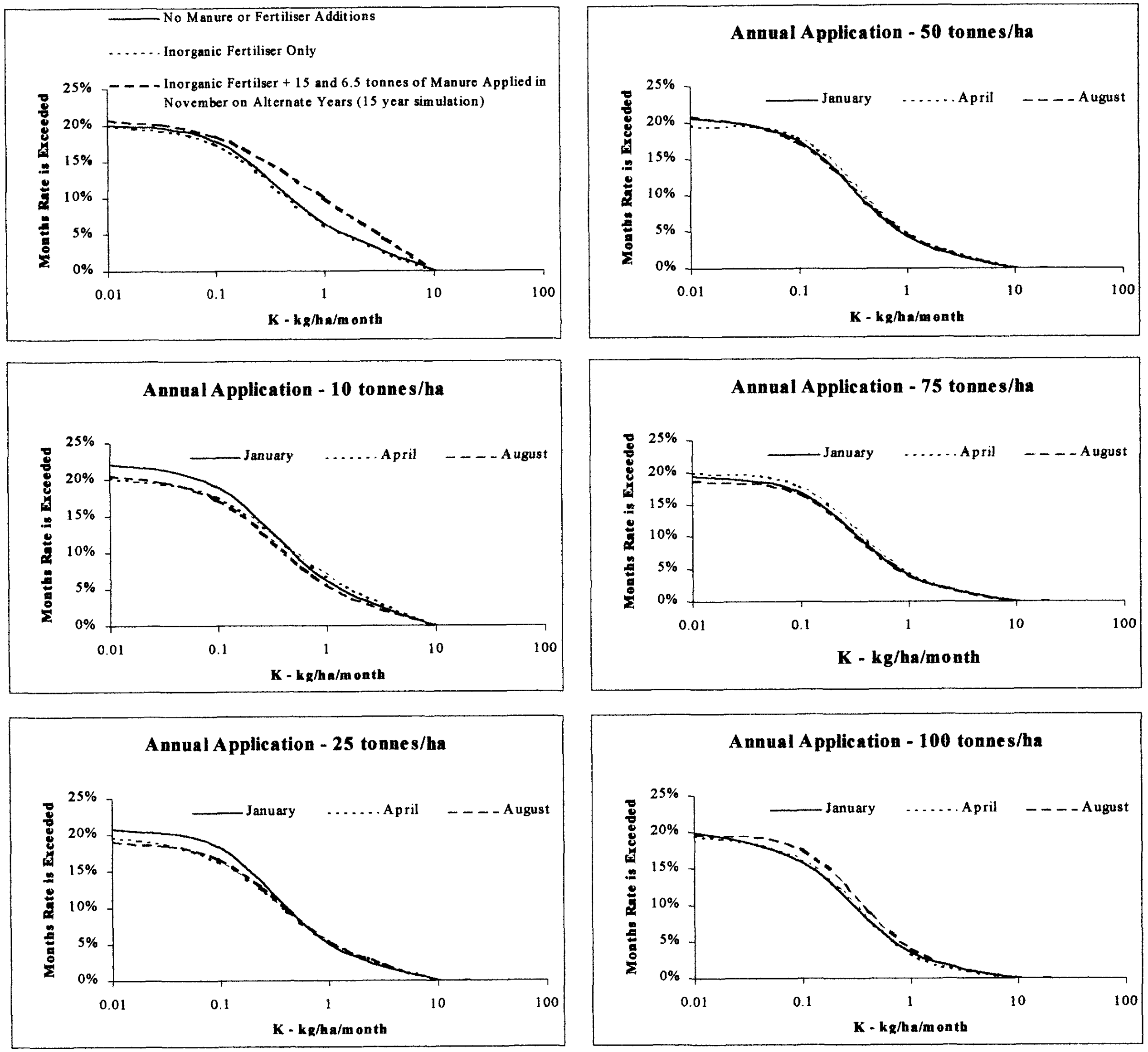


Figure 8.14. Cumulative Density Function of K Removed in Runoff per Month

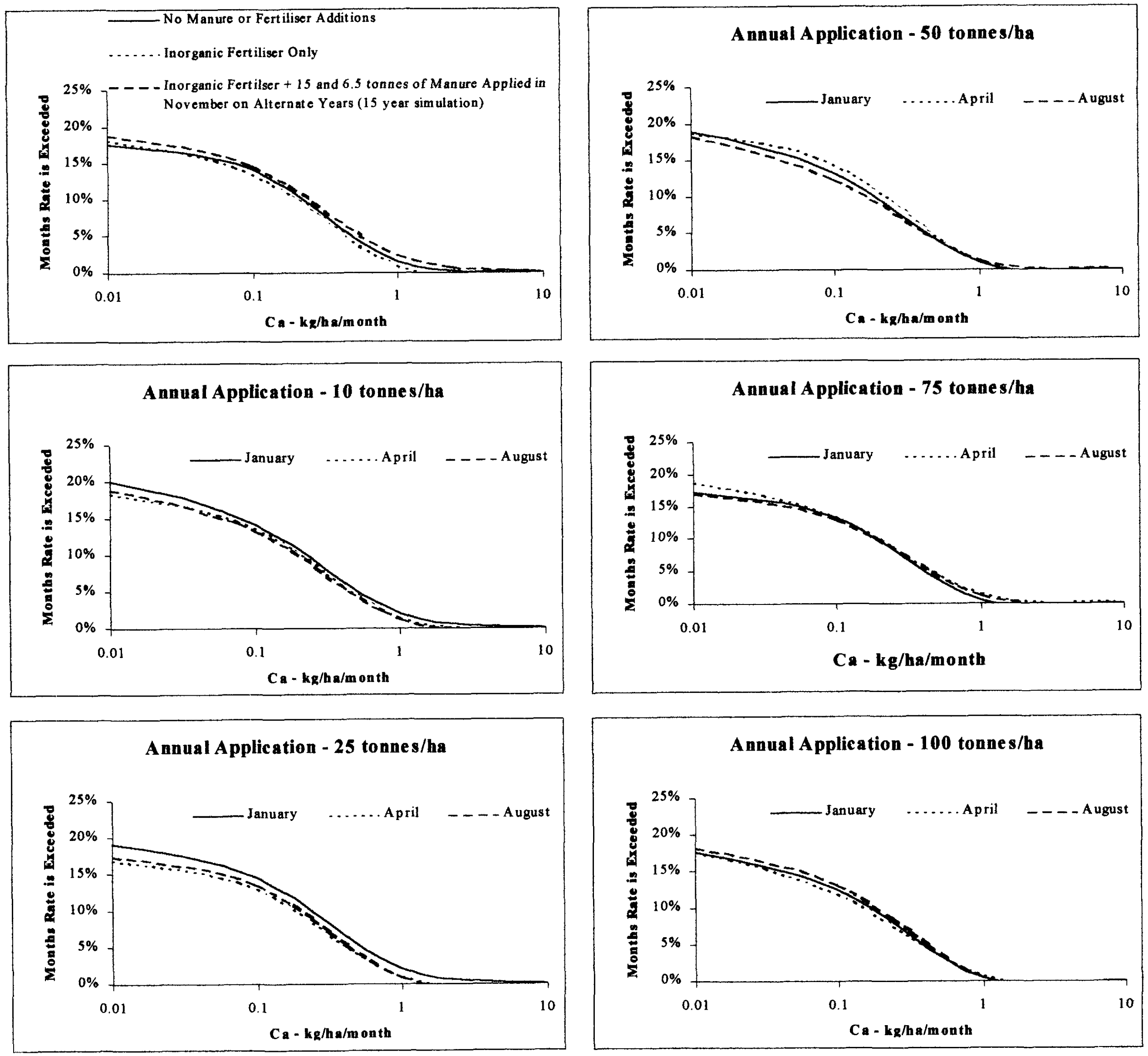


Figure 8.15. Cumulative Density Function of Ca Removed in Runoff per Month

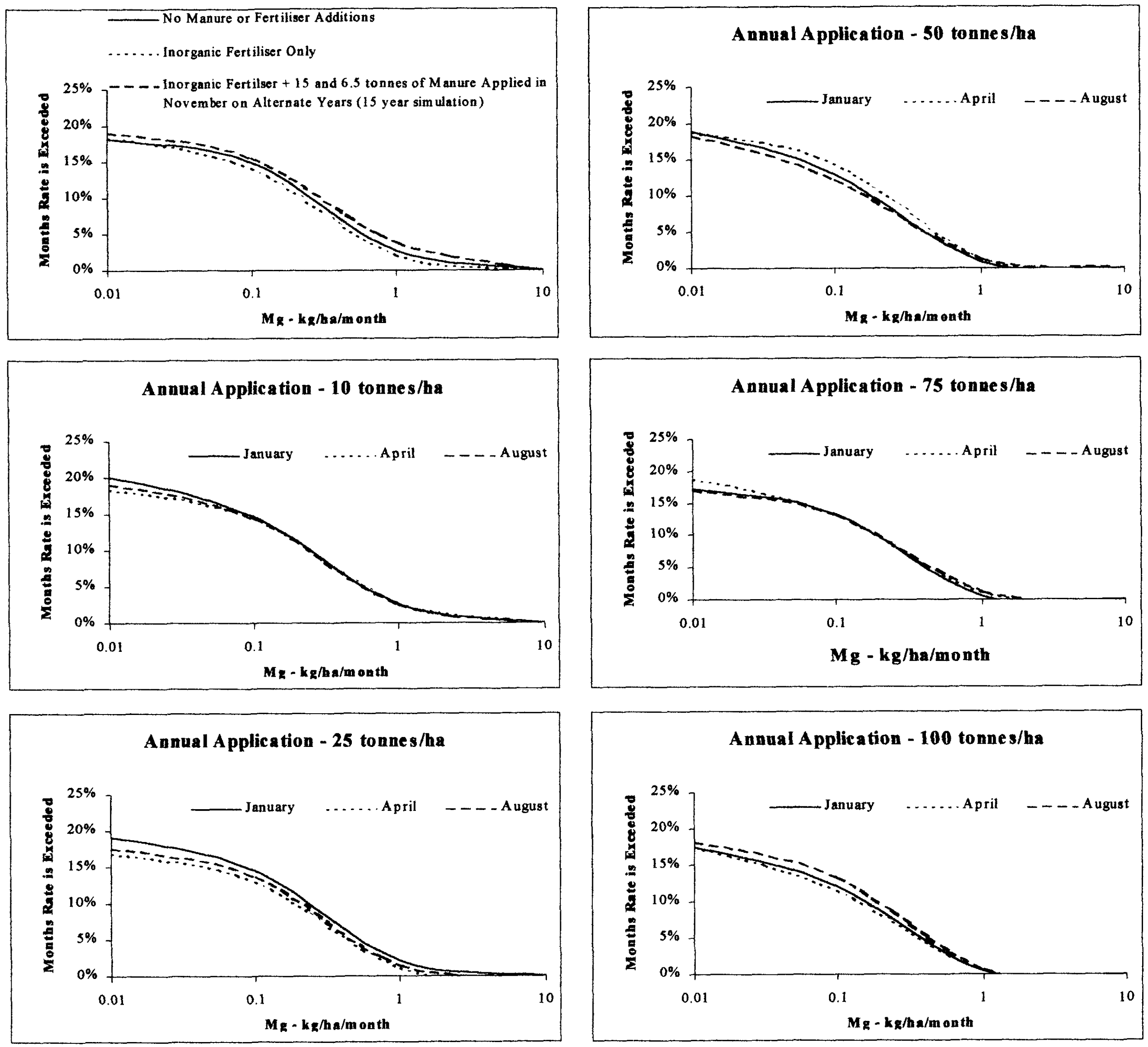


Figure 8.16. Cumulative Density Function of Mg Removed in Runoff per Month

Comparing the total cations removed in runoff over the 6-year simulations across all the treatments, as shown in Figure 8.17, supports the observed trend for Mg and Ca. Figure 8.18 is a box whisker plot for all treatments, showing the variation within the treatments. This figure reinforces an apparent lower runoff of K, Ca and Mg for the 100 tonnes/ha manure application rates, whether applied in January, April or August. These runoff totals are significant for K, Mg and Ca ($p<0.05$, Appendix N), and there is significantly less of these cations removed in runoff over the six years for the 100 tonnes/ha compared to all other treatments. These and other differences are summarised in Table 8.2, which indicates that for most treatments, the cation most affected is Mg, with K being the next cation, followed by Ca.

Table 8.2. Significant Difference Between Application Rates ($p<0.05$) for K, Ca and Mg

		No manure (0)	Inorganic (1)	15/6	10	25	50	75	100
				tonnes/ha of manure					
No manure (0)							Mg	Mg	K, Ca & Mg
Inorganic (1)					K & Mg			Mg	K, Ca & Mg
15/6					K & Mg			Mg	K, Ca & Mg
10							K & Mg	K & Mg	K, Ca & Mg
25								Mg	K, Ca & Mg
50	tonnes/ha								K, Ca & Mg
75									K, Ca & Mg
100									

The significant differences in the totals of K removed in the runoff (Appendix N) are not obvious in the cumulative density function of the totals of K removed in any month (see Figure 8.14). This highlights the importance of looking at output data from a different perspective to give a complete picture of the effects of adding manure and effluent.

Investigating the average concentration of each nutrient in runoff for each month should provide an insight into the behaviour of the system and highlight the months when extra care is required for a manure and effluent utilisation system. The inclusion of the average monthly totals for runoff in Figure 8.19 indicates that differences occur across the treatments due to the stochastic nature of the system. It is therefore not possible to compare the total amounts removed each month for each treatment. The average cation concentration in the runoff is therefore used to compare treatments, shown in Figure 8.19 for each of the four cations, for each month and each treatment.

The first column of graphs in Figure 8.19 indicates that runoff quantities are maximum during January, February, March, May and October. For all treatments these months were associated with relatively high concentrations of each cation in the runoff. The highest concentration for all cations and treatments occurred during the month of April, which coincided with minimal runoff. Gross amounts of cations removed is dependent on concentration and runoff quantities, thus, during April, the total cations removed may be less than months with moderate runoff and moderate cation concentrations. Figure 8.19 also supports the result above, with less K, Mg and Ca in runoff as the application rates increase.

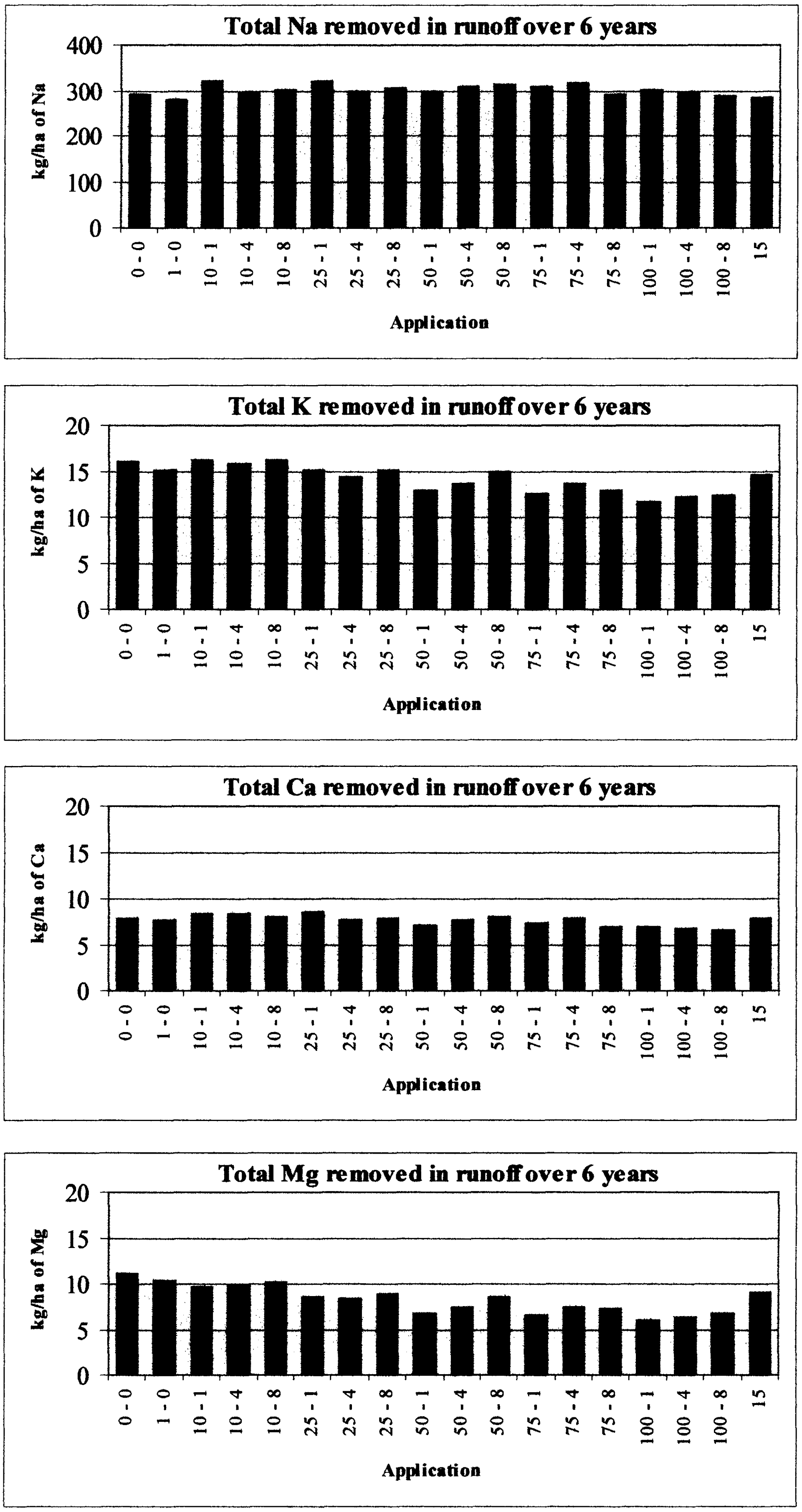


Figure 8.17. Average of Total Amount of Each Cation Removed in Runoff Over a 6 Year Simulation for all Treatments (20 replicates) (see Figure 8.9 for Legend of Application Treatments).

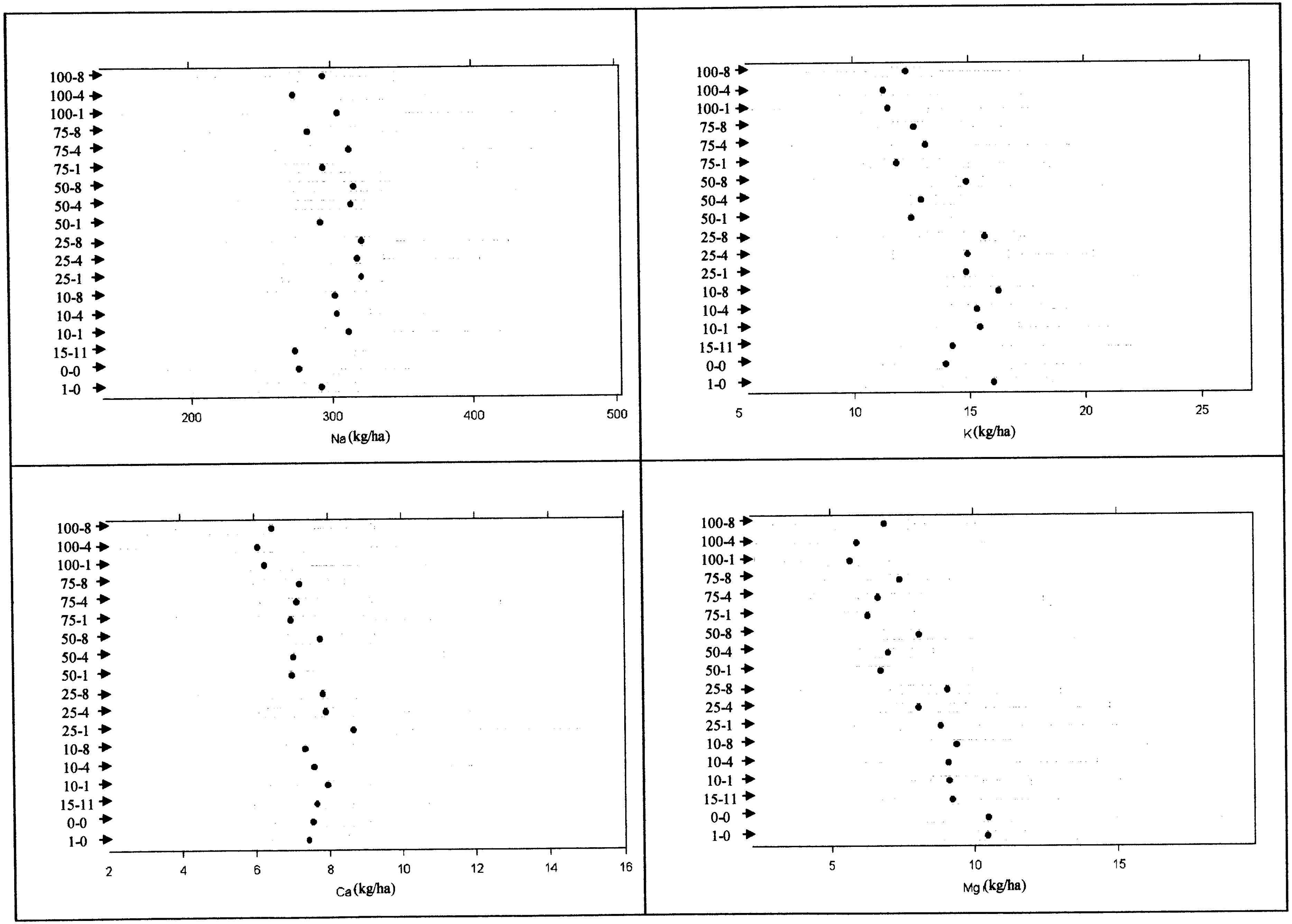


Figure 8.18. Box and Whisker Plots of Total Cations in Runoff Over 6 Year Simulations (20 Replicates of Each Treatment)

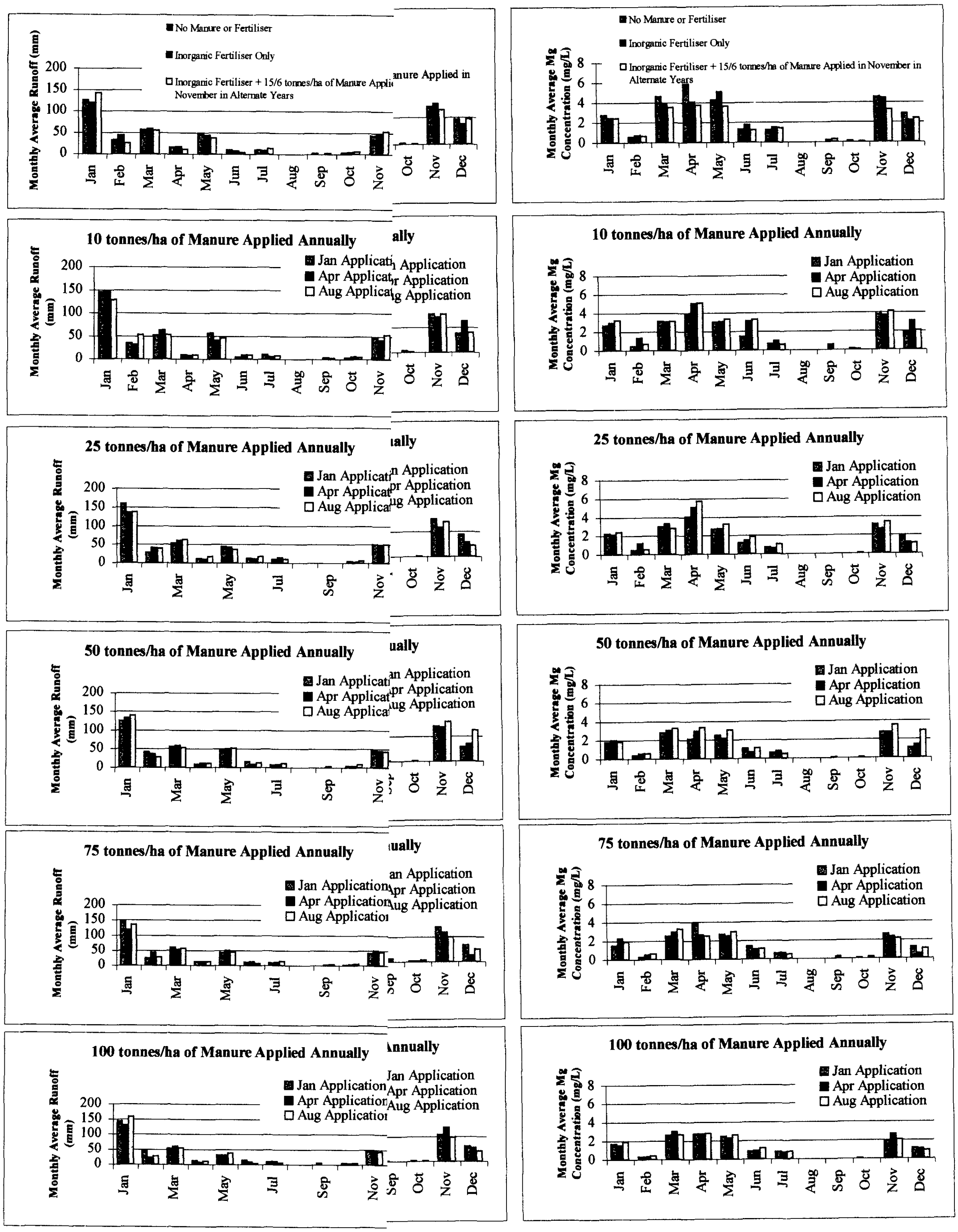


Figure 8.19. Average Monthly Concentrati

8.2.1.2 Nitrogen and Phosphorus

The behaviour of both the inorganic and organic forms of N and P are first investigated by graphing their cumulative density functions for the amount of each nutrient lost in the runoff in any month. As shown in Figure 8.20, the probability of inorganic N lost increases with increasing rates of manure applied annually. For example, the probability of more than 10 kg/ha of inorganic N lost in runoff in any month increases from near 0 for the 10 tonnes/ha annual application rate to approximately 12% for the 100 tonnes/ha application rate. Figure 8.21 indicates that there are minimal differences for the probability of the loss of organic N in runoff in any given month.

The cumulative density graphs of the amount of both forms of P lost in runoff in any given month are shown in Figure 8.22 and Figure 8.23. These graphs indicate that there is little difference in the amount of both forms of P that is lost in the runoff, as a function of the treatment. When inorganic P is added in either the effluent or manure it is only available for loss in runoff on the day of application, after which it is transformed to the organic form. Further developments of the model that include an erosion module and more sophisticated P transformation algorithms will enhance the value of the model output for the levels of P lost in runoff. These same comments apply to organic N losses in runoff.

Figure 8.24 is the average inorganic and organic N and P concentrations in the runoff for each month of the year, with total runoff for each month. These figures highlight the difference in inorganic N in runoff for the range of different manure application rates. There are also some apparent differences for application timing and loss of inorganic N, with 3 to 4 times the concentration of inorganic N in the runoff in March when the manure is applied in August compared, with January or April applications. However, for April applications, the concentration of inorganic N in the runoff during October, November and December is 2 to 3 times higher than for applications that occurred in January or August. This is a function of modelling the mineralisation process and highlights the many factors that need to be addressed when deciding the time for application, even when only one element is considered.

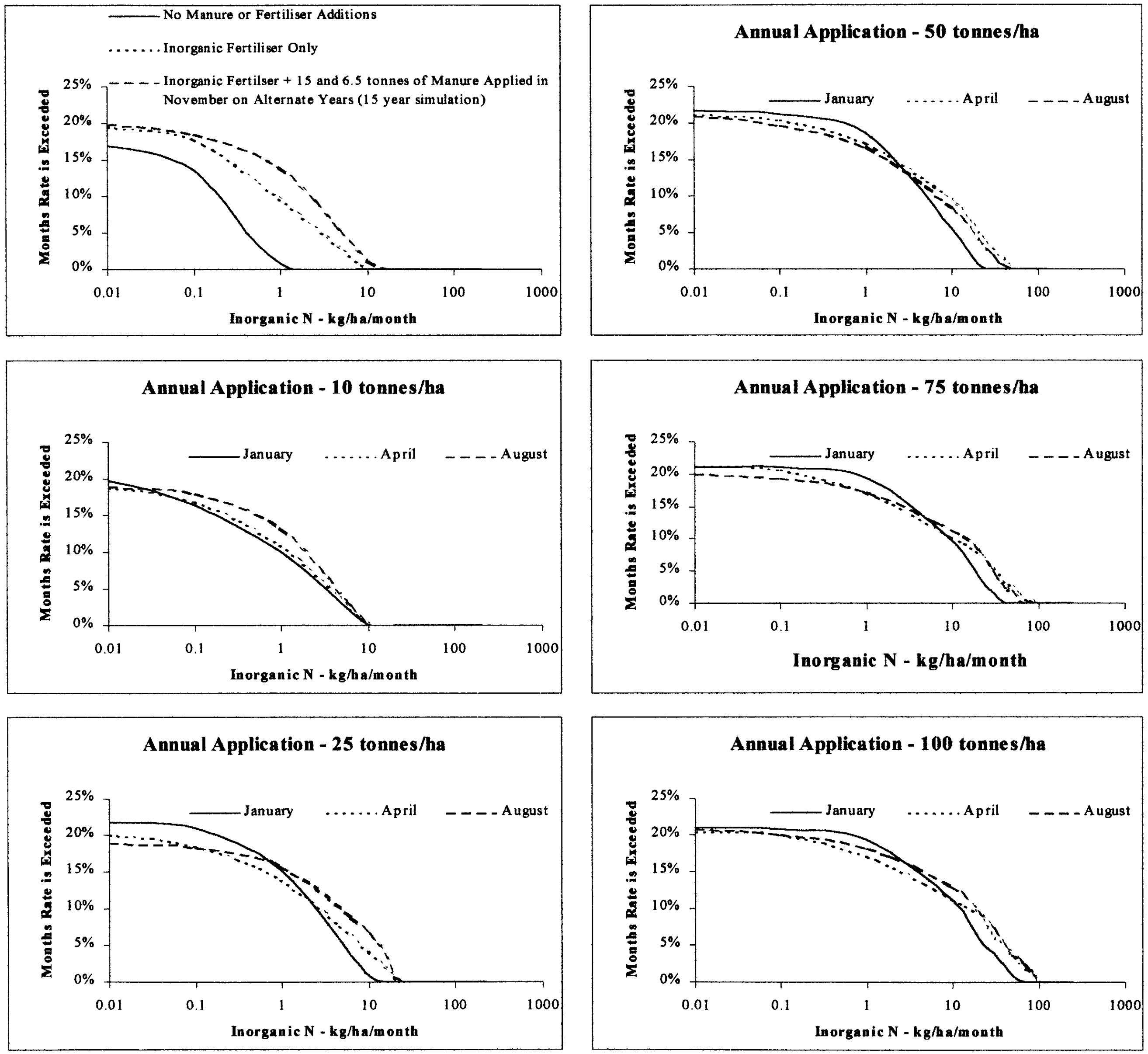


Figure 8.20. Cumulative Density Function of Inorganic N Removed in Runoff per Month

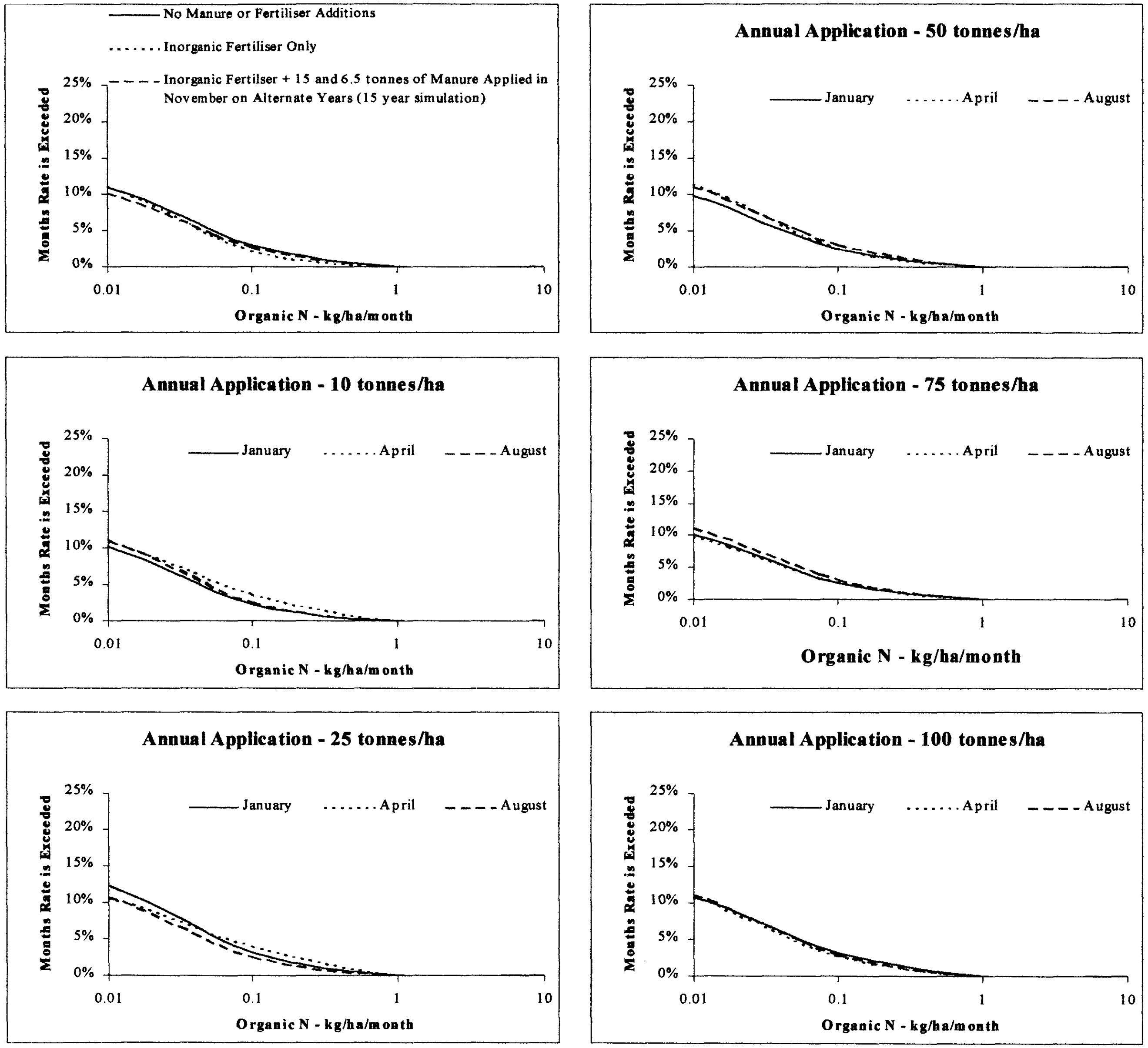


Figure 8.21. Cumulative Density Function of Organic N Removed in Runoff per Month

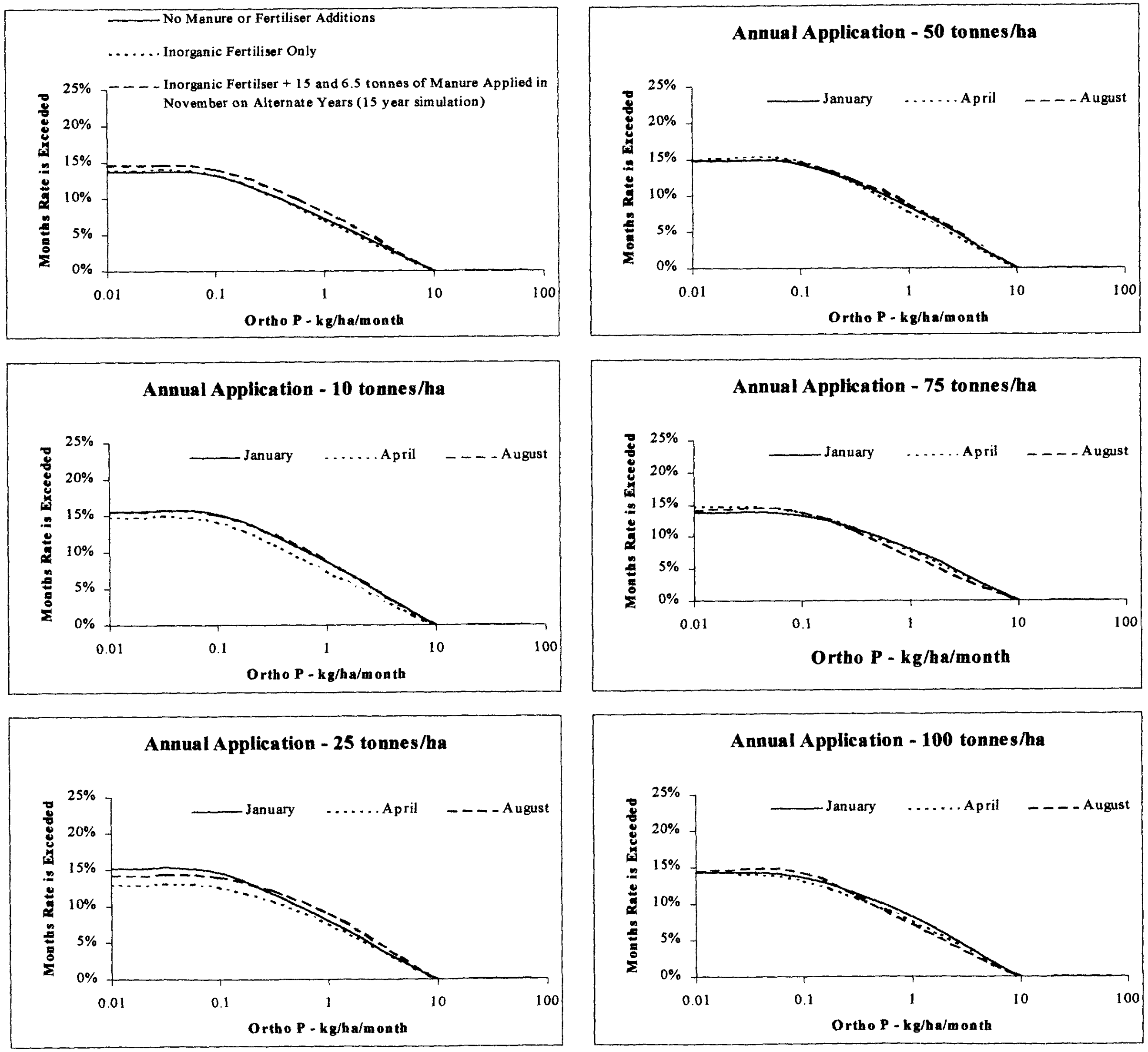


Figure 8.22. Cumulative Density Function of Ortho P Removed in Runoff per Month

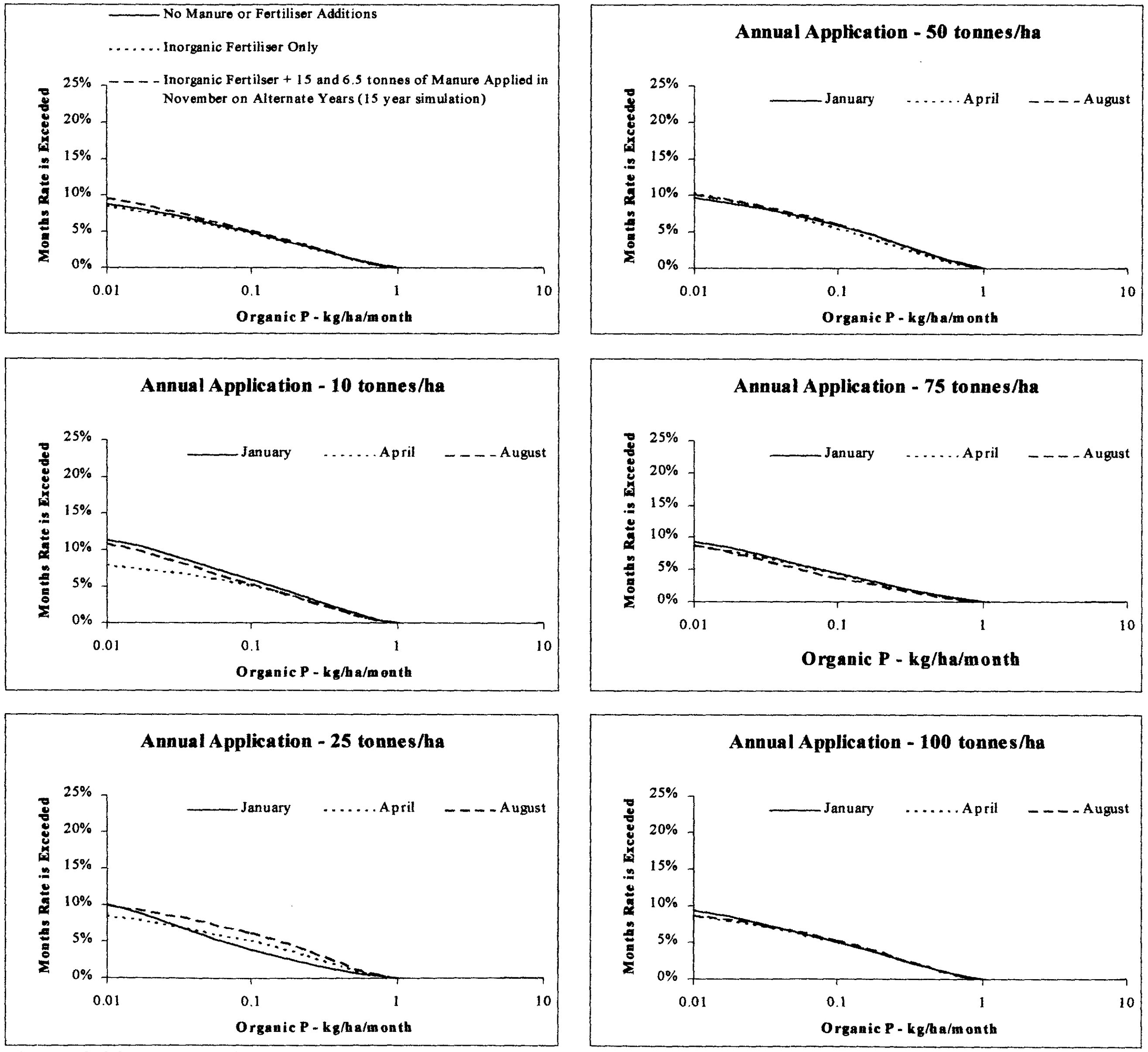


Figure 8.23. Cumulative Density Function of Organic P Removed in Runoff per Month

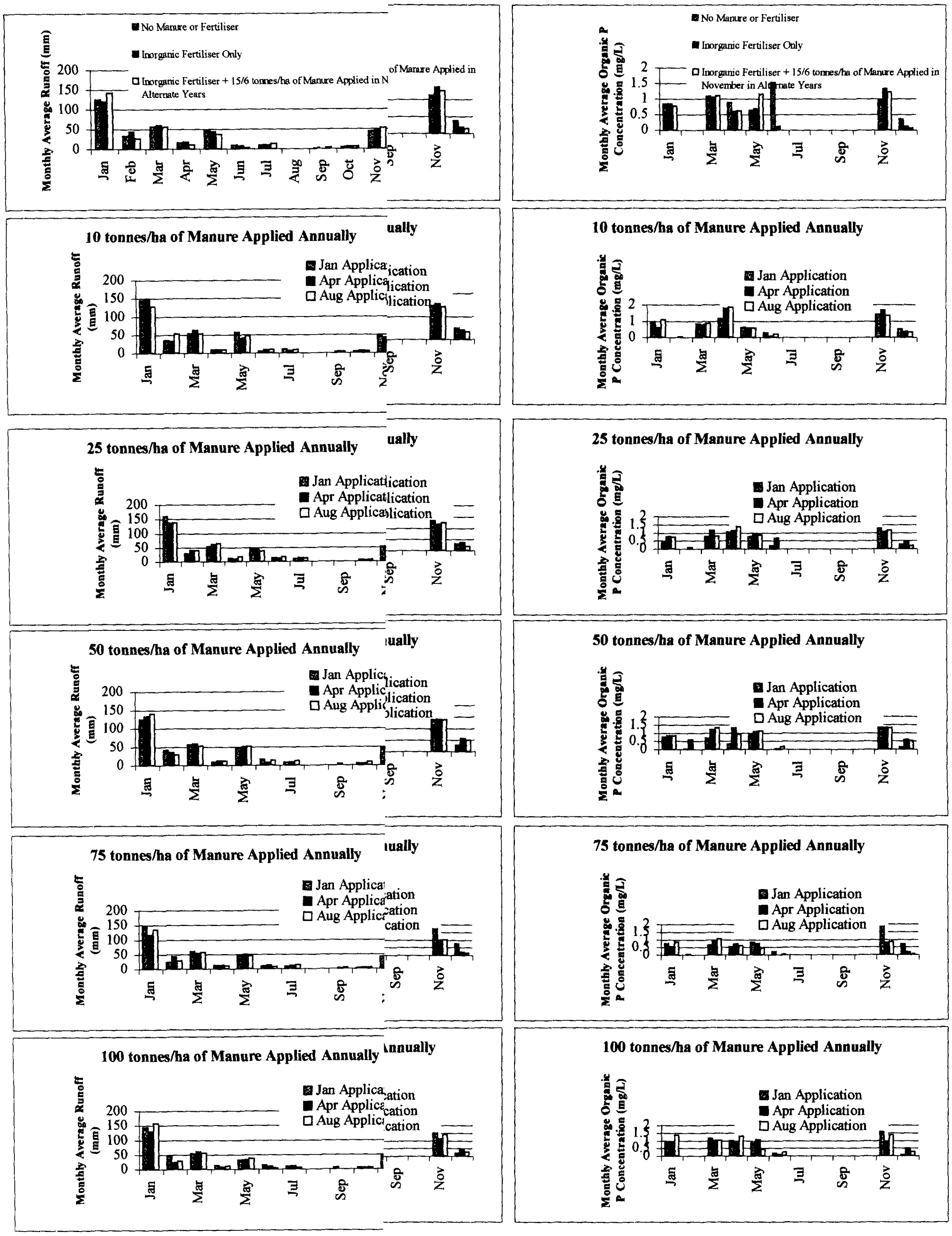


Figure 8.24. Monthly Average Runoff Tot

Figure 8.25 and Figure 8.26 graph the average cumulative totals of N and P removed in runoff for the 6-year simulations. Total losses of N are approximately 100kg/ha less when manure is applied in January, compared with April and August applications for all manure application rates. However, there is no significant difference (p>0.05) for the loss of total P between the difference treatments (Appendix O).

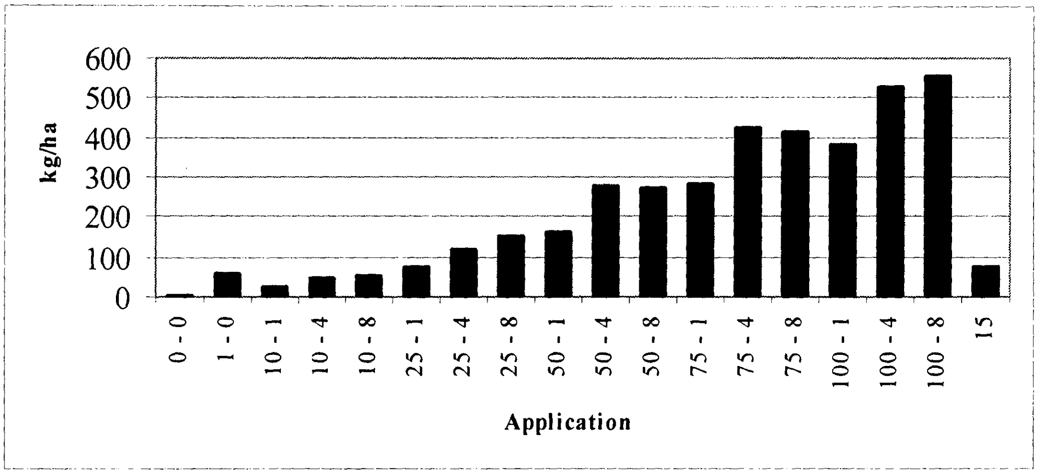


Figure 8.25. Total Amount of N (kg/ha) Removed in Runoff Over a Six-Year Simulation for all Treatments

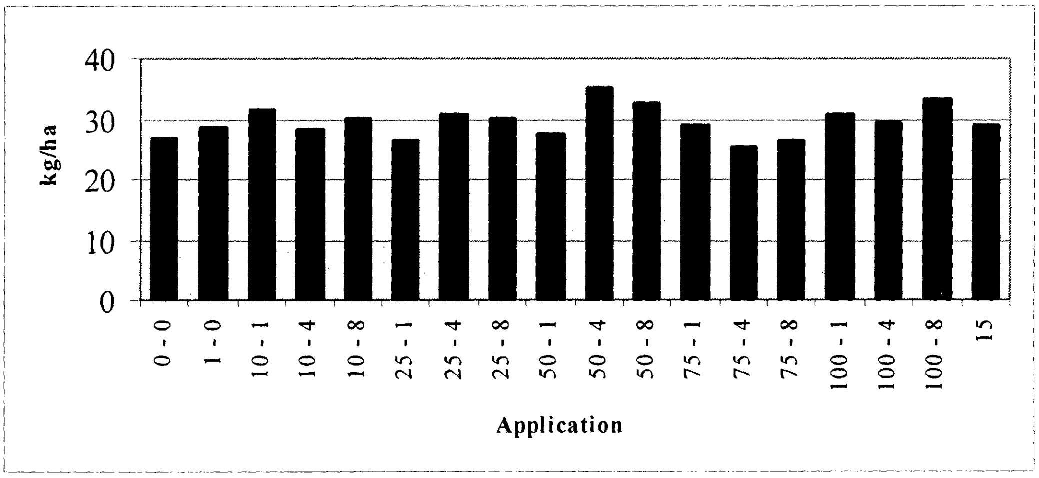


Figure 8.26. Total Amount of P (kg/ha) Removed in Runoff Over a Six-Year Simulation for all Treatments

8.2.2 Drainage

The total drainage depth is investigated using the 6-year simulations for each treatment. ANOVA results of a comparison of these total drainage depths, presented in Table 8.3, indicate no significant difference between treatments. However, as shown in Figure 8.27 there is considerable variation across the treatments as a result of the stochastic nature of the model.

Table 8.3. "S-plus" Analysis of Variance Output for Differences in Drainage Totals Over Six Year Simulations (20 Replicates for Each Treatment)

```
*** Analysis of Variance Model ***
           Df Sum of Sq  Mean Sq  F Value      Pr(F)
      rate  1      2000  1999.97 0.076636 0.7820714
     month  4    104744 26185.88 1.003409 0.4057077
rate:month  3    156677 52225.67 2.001220 0.1135058
 Residuals 351  9160019 26096.92
```

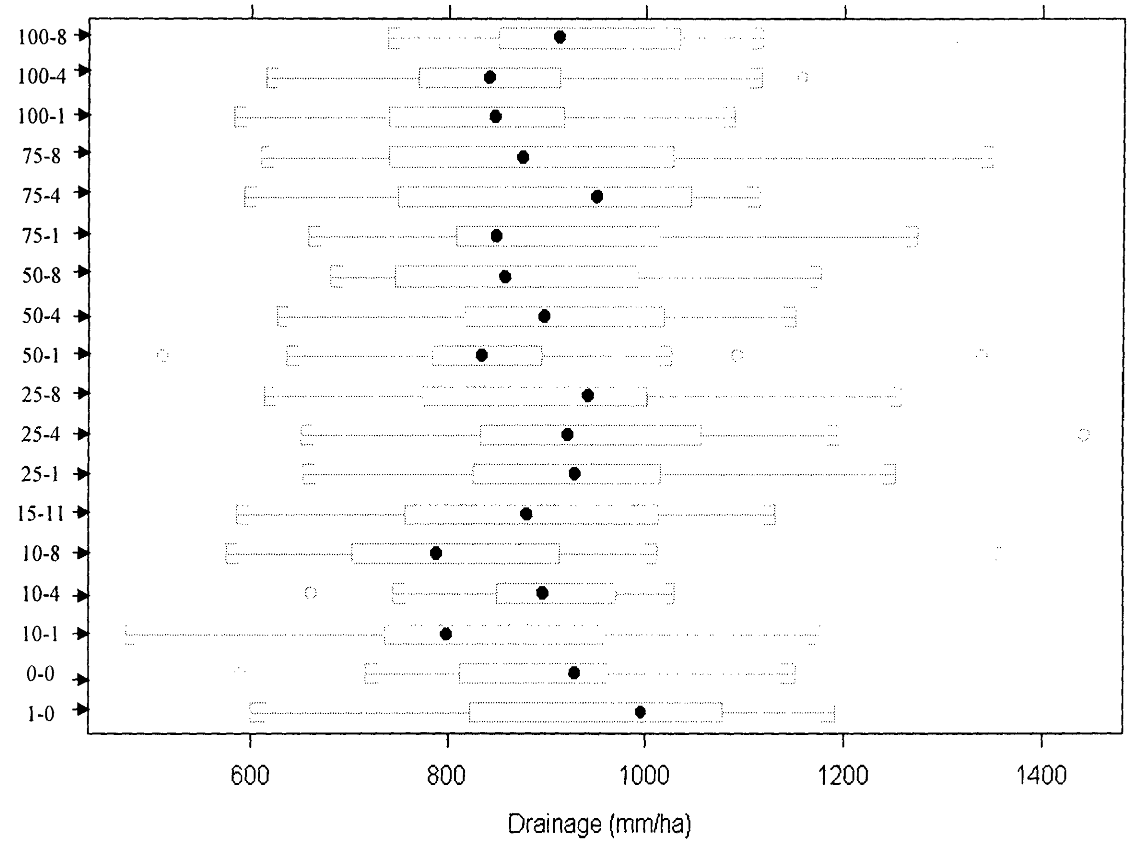


Figure 8.27. Box and Whisker Plots of Total Drainage Depths (mm) for Each Treatment (20 Replicates)

Figure 8.28 is a cumulative density function of drainage in any given month and a similar picture emerges as for the runoff graphs (see Figure 8.12), which is again a function of the stochastic nature of the model. The probability of more than 10 mm of drainage in any month is around 25% for all treatments. In comparison, there is a 15-20% probability of runoff being greater than 10 mm/ha in any month, which indicates that there is a greater potential for nutrients to be lost via the drainage pathway then via the runoff pathway.

The first graph in Figure 8.28 compares the no manure or fertiliser treatment with the inorganic fertiliser only treatment and the first 6 years of the 15 year simulation, which included manure applied at the rate of 15 and 6.5 tonnes/ha on alternate years plus inorganic fertiliser. These curves coincide over the range of values, however when comparing the first graphs of the cumulative density functions for each of the nutrients removed in drainage on any month, shown in Figure 8.29 to Figure 8.32, there is considerable difference between treatments. For Na, Ca and Mg, there is a 10% greater possibility that there will be more than 0.01 kg/ha lost in drainage for the inorganic fertiliser + 15/6.5 tonnes/ha treatment compared with the no manure or fertiliser treatment. The probability of greater than 0.01 kg/ha of Na, Ca and Mg lost in drainage for the inorganic fertiliser only treatment falls approximately between these two treatments. However, the probability of losing greater than 0.01 kg/ha of K on average per month is approximately 10% less for the inorganic + 15/6.5 tonnes/ha treatment then for the no manure treatment. This occurs because in the 15-year simulation, the K is diminished in the A2 and B horizons by the sixth year (see Figure 8.1) and therefore the probabilities reduce because of the lack of K in solution for the remainder of the simulation. Between the other treatments there is little difference in the probability of losing any of the cations in drainage on any given month. There is also no significant difference in the total losses of cations in drainage ($p>0.05$, Appendix P) as shown in Figure 8.33.

Significant differences are apparent in the loss of N in drainage for the different application rates and time of application, shown in Figure 8.34. The biggest difference is between the inorganic +15/6.5 tonnes/ha treatment and the no manure or fertiliser treatment. For the other treatments, there is little difference between the time of application, except for the 50 tonnes/ha application which has an approximately 10% less probability of inorganic N being removed in runoff when the manure is applied in August to when it is applied in either January or April. There appears to be little difference in the probability of losing N in runoff when 50 tonnes/ha is applied in August compared to applying 25 tonnes/ha of manure in January, April or August.

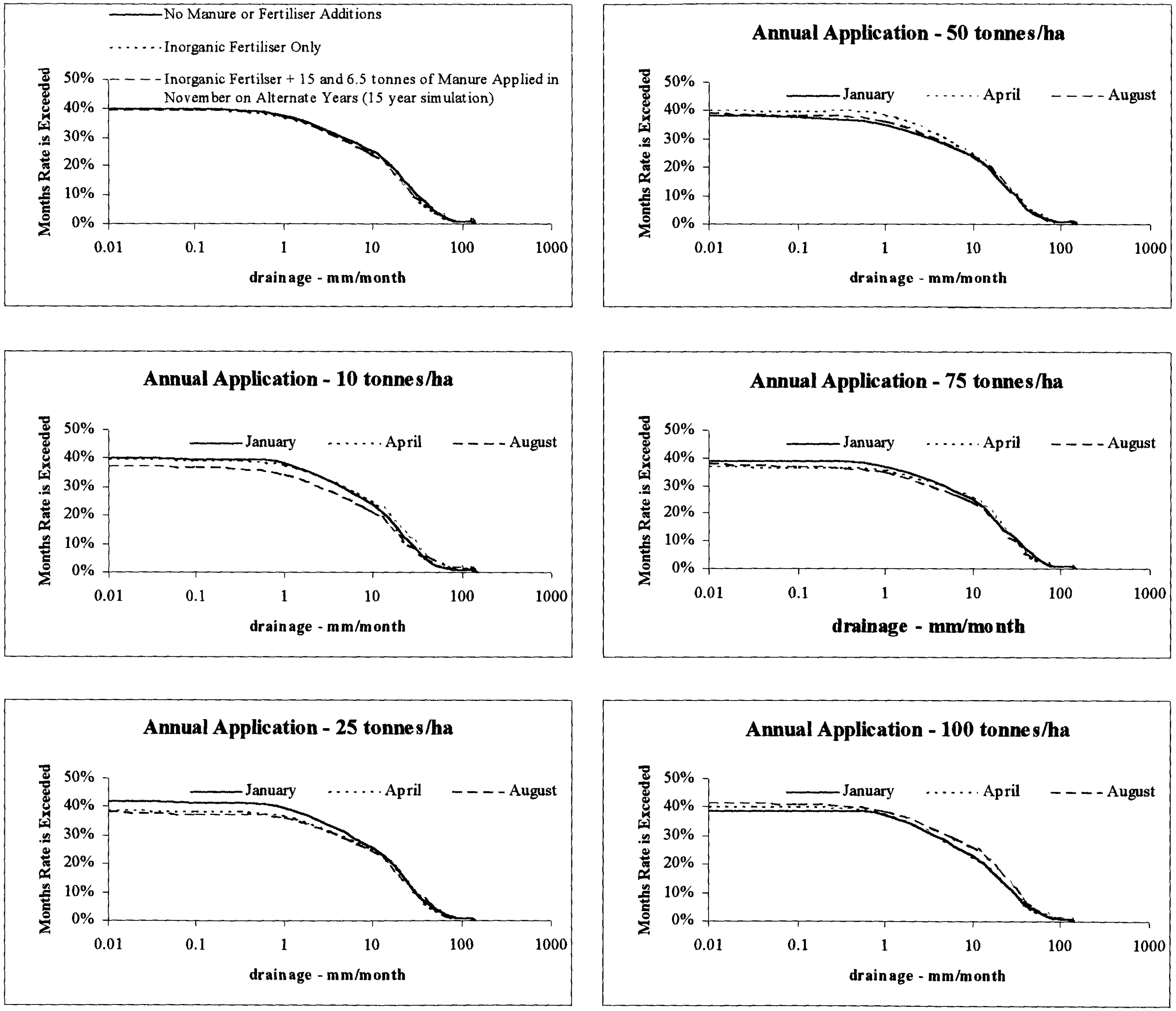


Figure 8.28. Cumulative Density Function of Drainage Depth per Month

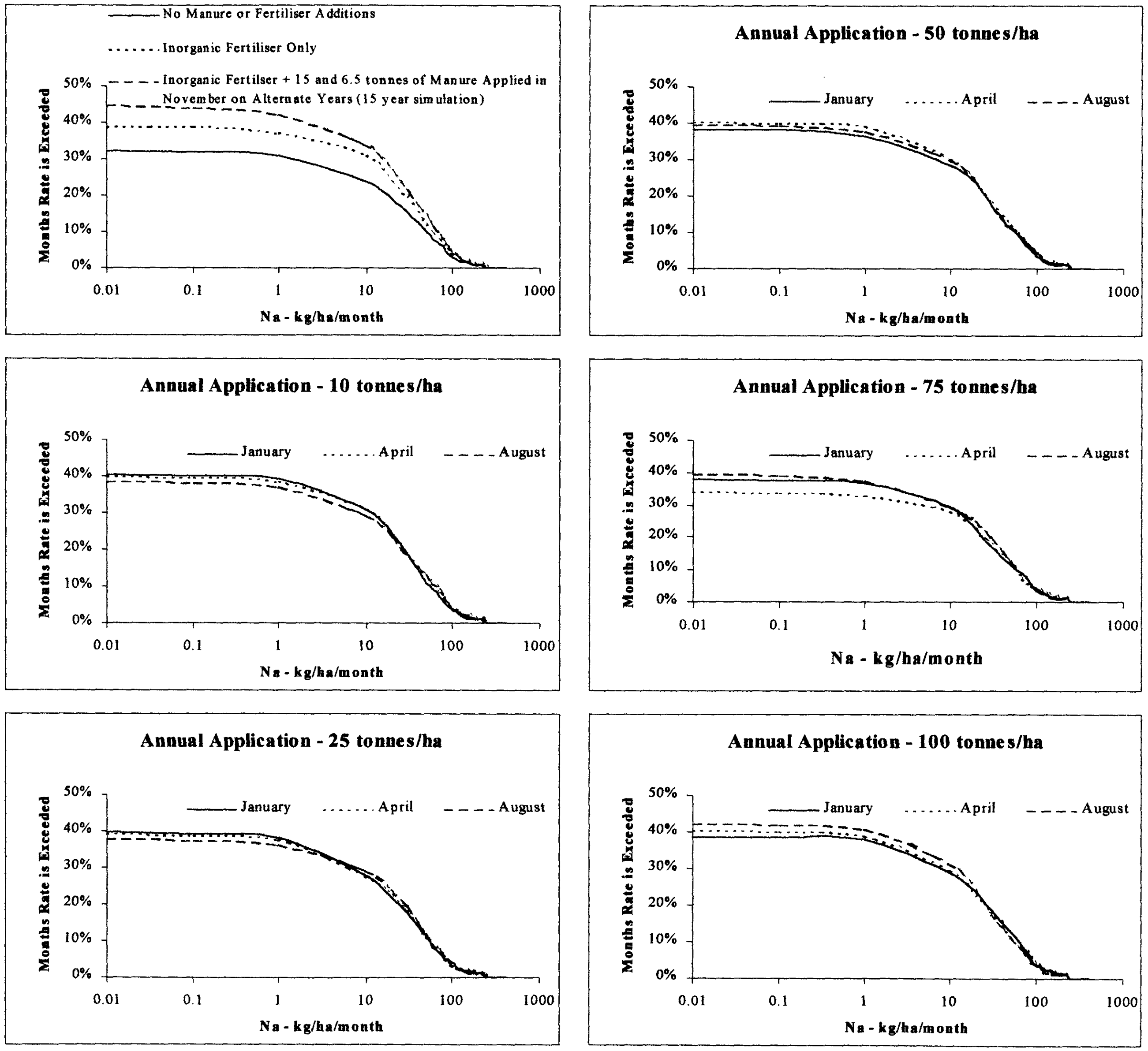


Figure 8.29. Cumulative Density Function of Na Removed in Drainage per Month

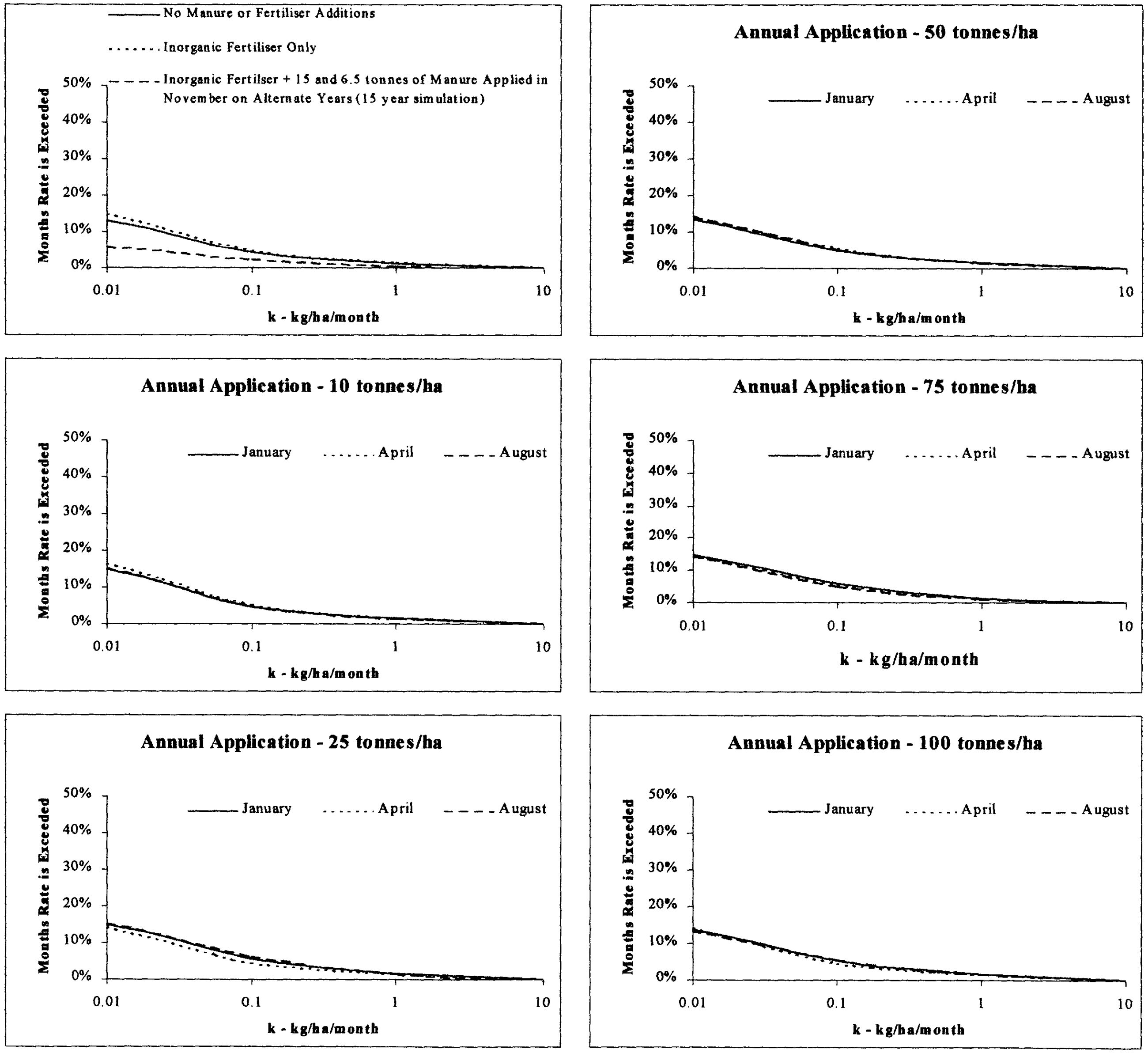


Figure 8.30. Cumulative Density Function of K Removed in Drainage per Month

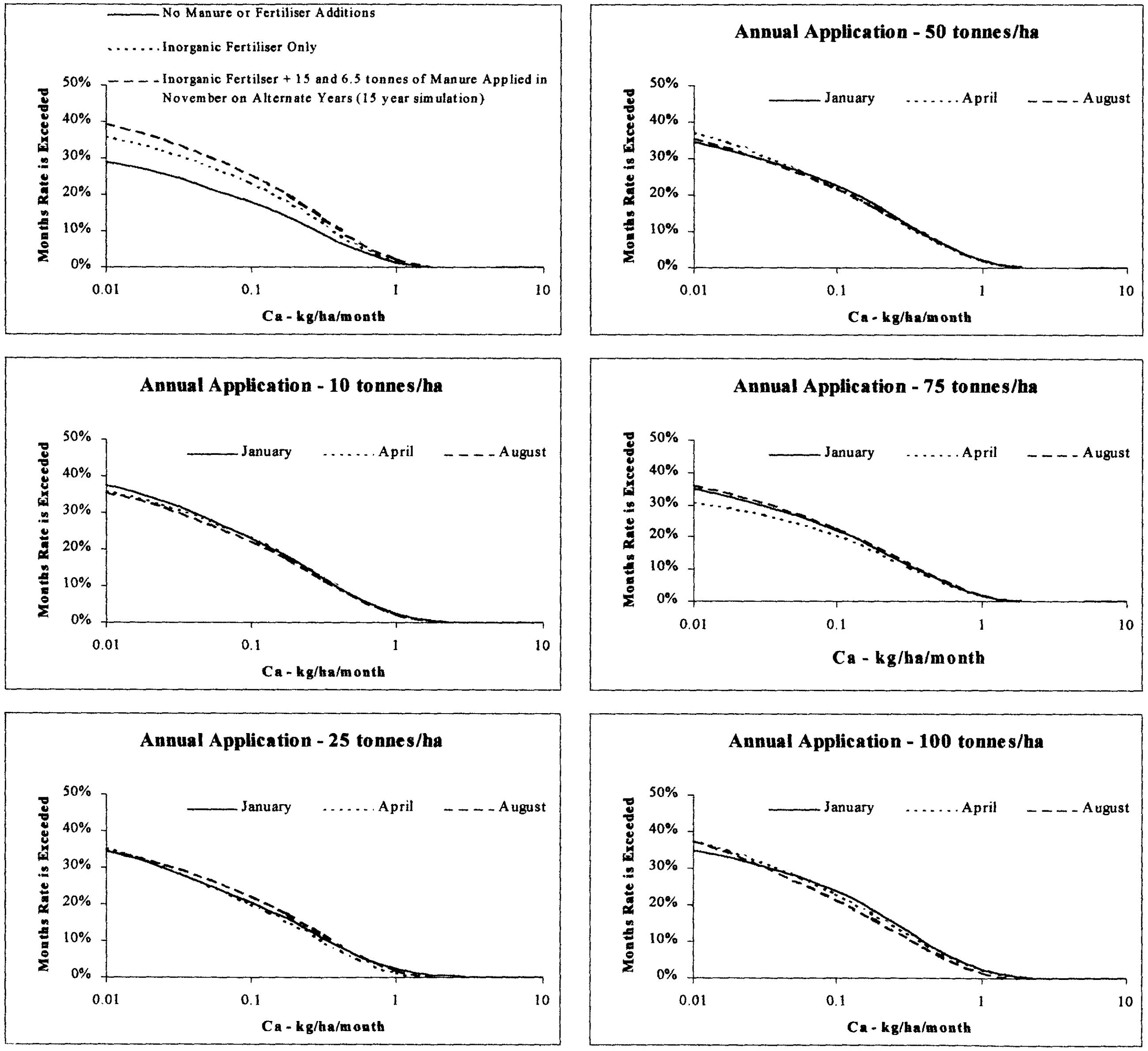


Figure 8.31. Cumulative Density Function of Ca Removed in Drainage per Month

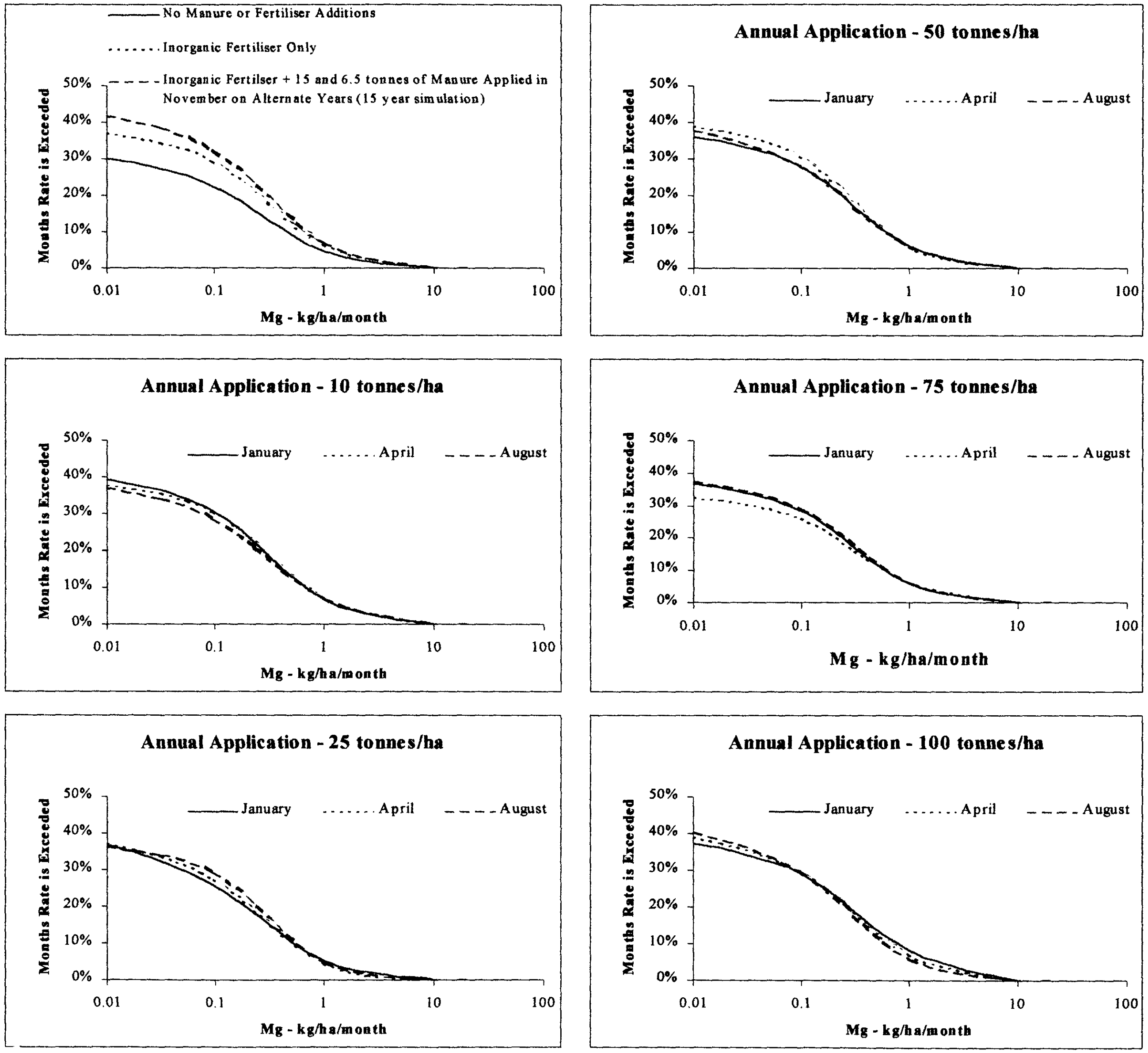
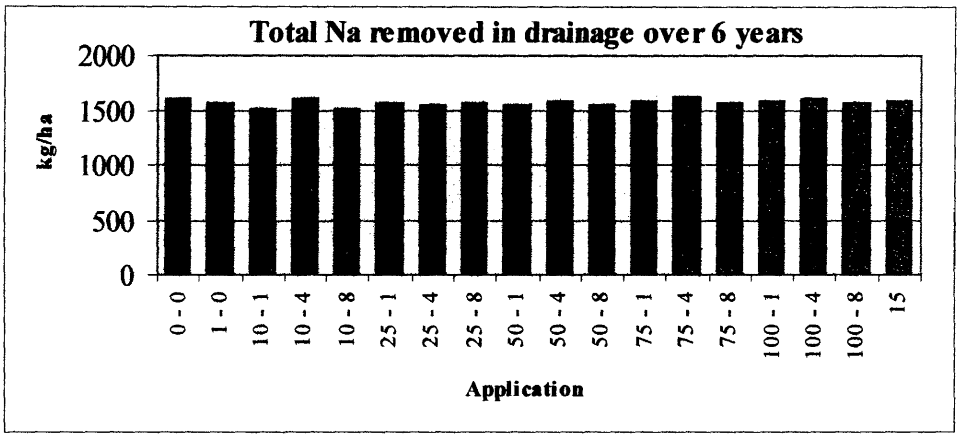
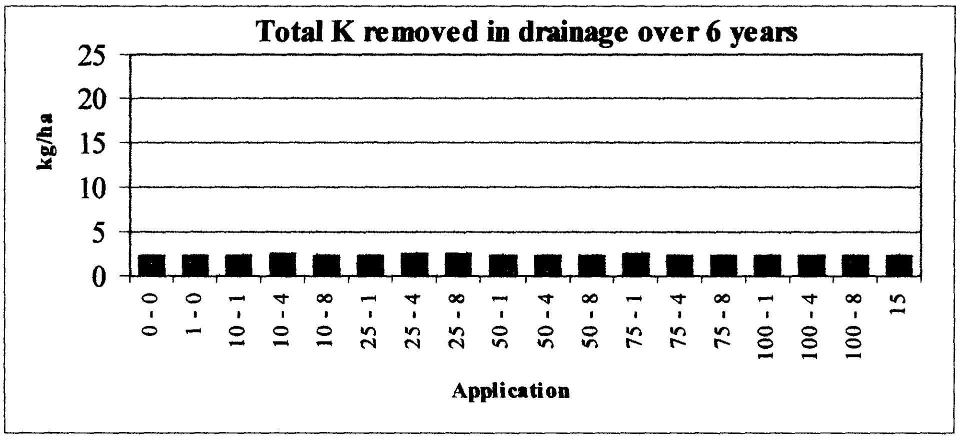
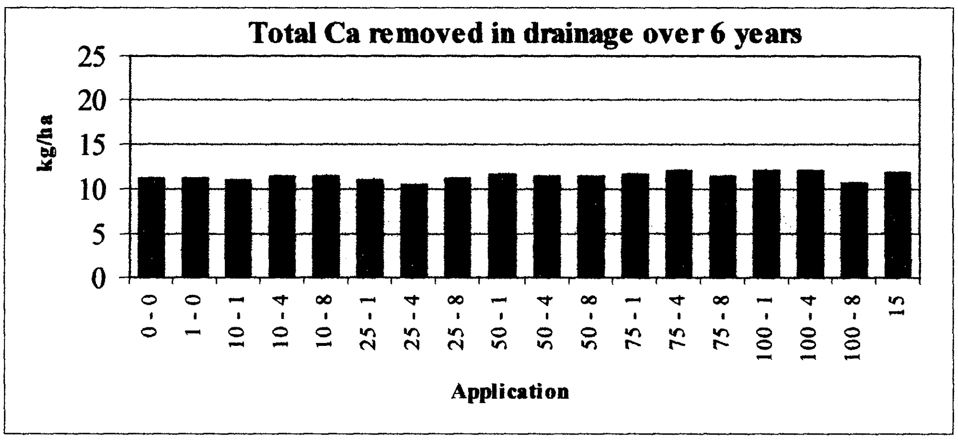


Figure 8.32. Cumulative Density Function of Mg Removed in Drainage per Month







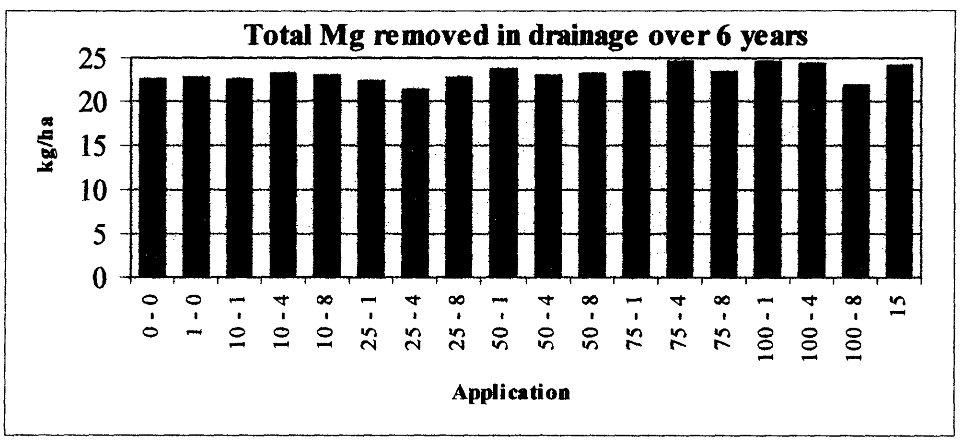


Figure 8.33. Average of Total Amount of Each Cation Removed in Drainage Over a 6Year Simulation for all Treatments (20 Replicates).

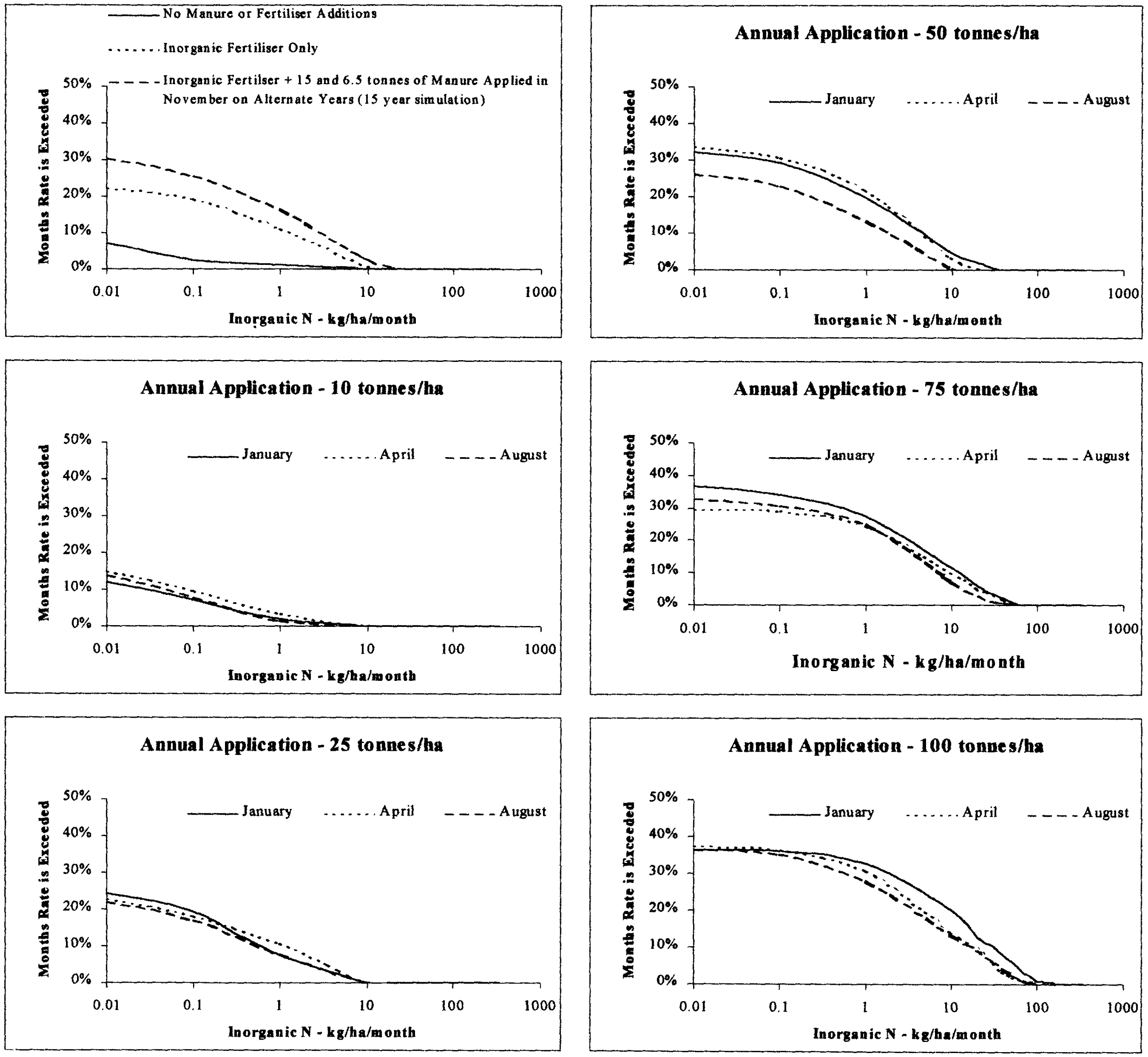


Figure 8.34. Cumulative Density Function of Inorganic N Removed in Drainage per Month

January application of manure results in considerably less N in runoff (see Figure 8.25), however in contrast to this, Figure 8.35 indicates that August applications of all manure rates results in considerable less N in drainage. This adds another complication in trying to determine the optimal application rates and time of manure application.

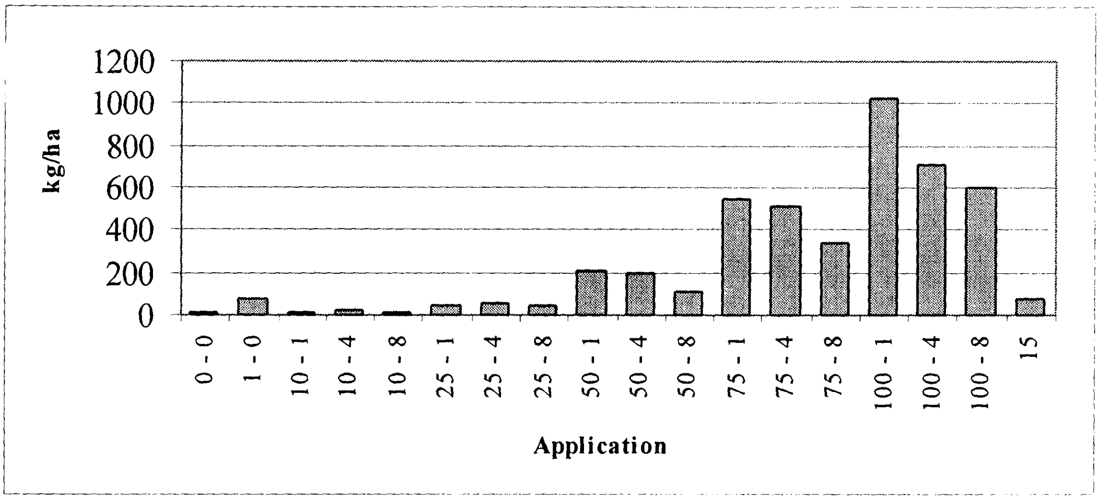


Figure 8.35. Average of Total Amount of Inorganic N (kg/ha) Removed in Drainage Over a Six Year Simulation for all Treatments (20 Replicates for Each Treatment)

Figure 8.36 shows the average of the total drainage depths lost per hectare for each month and the average concentration of cations in the drainage solutions. Compared with the runoff averages (see Figure 8.19), there are considerably more cations lost in drainage than runoff. The highest drainage occurred during January, March, September and October, with the average concentrations for these months being moderate to high for each cation. Therefore the potential losses via drainage are greatest during these months. The concentration of K in January is more than double the concentration for any of the other months for all treatments, with no apparent difference between treatments. However, this same difference is not evident for the other cations. This is important because of the depletion of K in the A2 and B horizon and the large K requirement of the crop, reinforcing the need to retain as much K in the profile as possible.

The June concentrations of Na, Ca and Mg for the inorganic + 15/6.5 tonnes/ha treatment is approximately double the concentrations for the no manure or fertiliser treatment and the inorganic fertiliser treatment only. The inorganic + 15/6.5 tonnes/ha treatment is obtained by averaging the 15 year simulation values as opposed to the 6 year simulation values for the other treatments. Therefore, the greater concentration could be a result of the greater variation in the concentration of these cations in the drainage solution in June.

Figure 8.36 indicates that the time of application of manure appears to have more of an effect for the 100 tonnes/ha application rate. At this rate, applying the manure in August will result in a smaller average concentration of all cations in the drainage for all months. The next best application time varies for different months and each cation. The only other consistent result is for the 10 tonnes/ha treatment, where the April application results in marginally less Na concentration in drainage. Figure 8.36 also indicates that there is little difference in the concentration of each cation in the drainage across the different treatments.

Figure 8.37 is the average monthly concentration of inorganic N in the drainage solution and indicates the much greater losses of N with increasing application rates. The average losses for treatments up to 50 tonnes/ha are considerably less than for 75 and 100 tonnes/ha treatments and nearly doubles from 50 to 75 to 100 tonnes/ha. For nearly every month, the August application yields less concentration of N in drainage than the January or April application, which supports the earlier finding of total losses of N over the 6 years being the least for the August application of each manure application rate (see Figure 8.35).

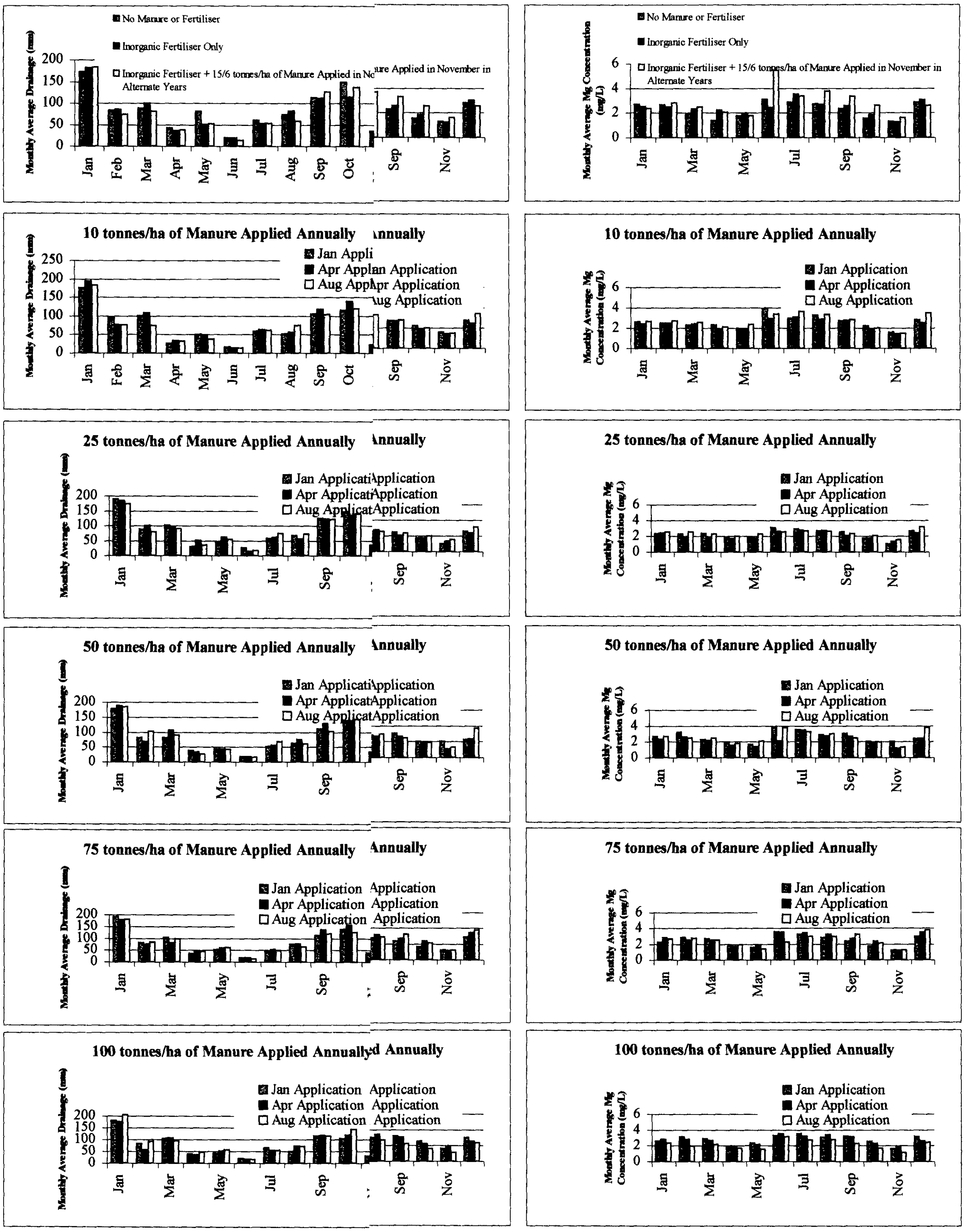


Figure 8.36. Average Monthly Drainage

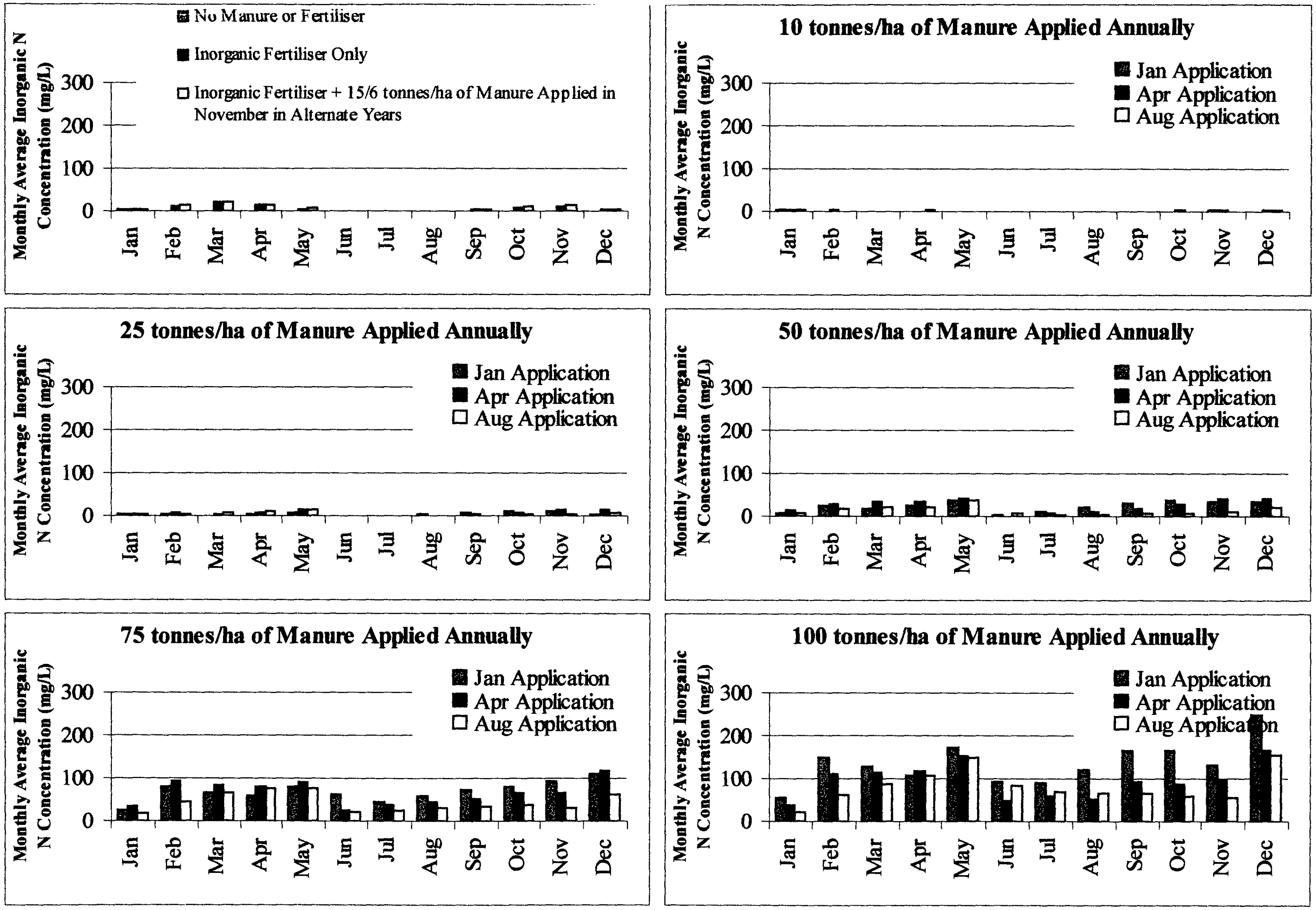


Figure 8.37. Average Monthly Concentration of Inorganic N in Drainage Solution for Each Treatment (20 Replicates)

8.3 Summary

From an environmental point of view the losses of N in runoff are least when manure is applied in January, compared with drainage losses for which the least losses occur when the manure is applied in August. For all the treatments except for the 75 and 100 tonnes/ha, the amounts lost in runoff are similar to the amounts lost in drainage. However, for the 75 and 100 tonnes/ha rates, the total amount of N lost in drainage is nearly twice the amount lost in runoff. Therefore, the optimal time of application for these higher rates, when considering the losses of N, is August. For the other rates, August or January applications will yield similar overall losses.

In terms of the production system, the losses of K are important as the crop has a high demand for this nutrient. There are no significant differences for the total losses through drainage of K, or the other cations, over the 6 years simulated. However, at the 100 tonnes/ha application rate, August is the optimal time for applying manure as this results in the least concentration in the drainage for all months for K and the other cations modelled. At the other application rates, the results are too variable to provide an estimate of the optimal application time.

Losses of K are greater through runoff than through drainage and the higher the application rate, the lower the total K removed in runoff, with January applications generally resulting in the least amount of K lost. The same result was found for Ca and Mg, with little apparent difference in the amount of Na lost through runoff. However, there is considerably more Na lost in drainage (approx 1500 kg/ha in drainage compared with 300 kg/ha in runoff) and slightly more Ca and Mg lost in drainage than runoff.

A subjective assessment of the results presented suggests that a manure application rate of 50 tonnes/ha applied in August to January will yield the most favourable conditions for the environment and the production system. This assessment is determined by balancing the increases in the N losses for the increasing application rates with the decreases in the losses of K, Ca and Mg with increased application rates.

Even though the effects of adding N and P in manure and effluent cannot be ignored, these effects are generally evident early on and agronomic measures can be taken to ensure that the effects are minimised. However, the effects of the cation imbalance is insidious and requires a closer monitoring of the whole system to ensure that any changes likely to be detrimental to the system are highlighted in a timely fashion, so that remedial action can be taken. Using the EMU model on a regular basis will give an indication of a likely system imbalance. In the 15 year simulation carried out on the Tullimba feedlot, the EMU model predicts the cations in the soil will reach a new equilibrium in approximately 11 years, based on the current management practices. The predicted reduction of Ca and increases in Mg suggest that additions of gypsum will be required.

The EMU model has highlighted the flaw in the current policy of the NSW EPA (Patterson, B. 1999, pers. comm., 26 Feb) of nil drainage. The model predicts that there is little difference in the Na losses in drainage, regardless of the manure application rate. If this Na is not leached through the profile, then the likely effect will be a reduction in yield resulting in less crop uptake and therefore greater potential losses of other nutrients. However, as most of the Na is added in the effluent, a system that removes the Na from the effluent before it is applied to the land would be of benefit to the overall production and environmental system. The model outputs highlights that research into a hydroponic system that grows a halophyte (such as salt bush), which preferentially takes up Na and results in a solution with a lesser Na concentration is required.

Chapter 9. Conclusions and Recommendations

9.1 Conclusions

Sustainability deals with the future. The future has always been, and no doubt will always be uncertain and any attempt to quantify the sustainability of a system must include this uncertainty. The EMU model developed in this study provides a predictive tool, which can be used to investigate agricultural management practices to enhance the probability of a sustainable system utilising manure and effluent.

Making decisions for managing sustainable systems requires an acceptance of uncertainty. When dealing with uncertainty, there is no measure that will give an absolute guarantee of the success or failure of a particular system. However, an understanding of the probable reactions of a system to inputs and outputs that change the system's equilibrium will improve the decision making process. One of the objectives of this research was to develop computer tools that aid this process.

The environmental impacts of cattle feedlot operations in Australia have been under scrutiny since the rapid industry expansion in the mid 1980s. As a consequence, regulatory authorities require feedlot operations to undertake intensive monitoring of their surrounds to ensure the greater environment is not degraded from the nutrients in manure and effluent. As a result of this monitoring, data collected by feedlot operators is becoming extensive and comprehensive. Regulatory authorities have traditionally undertaken review of these data, however, more emphasis is being placed on feedlot operators to maintain and interpret their monitoring results.

A major part of the research was to develop an environmental monitoring database using Microsoft Access, which provided a secure, flexible and efficient data storage system. The breadth of data collected over time has increased for some samples types, and changed for others, requiring flexibility to ensure that these changes didn't render the database obsolete. This flexibility allows the data to be used for many different projects. An aim of the database was to provide an easy and user friendly graphical interface to allow the presentation of time series data. This allows the user to look at comparisons between soil, plant and water systems of the feedlot and beyond. Examples of the use of this interface as an investigative tool were shown in Chapter 4.

This database also incorporates an interface that uses a daily time step, to graphically simulate the inputs, changes of state and outputs of the nutrients and salts from the irrigation and manure utilisation areas. For a particular nutrient or salt to be included in the simulation, time series data are required from the soil, plant, effluent and manure. The database and interface were built using a systems approach with the aim to use the database outputs to provide prompt feedback from the soil plant system receiving manure and effluent. This feedback highlights the output pathways of importance for each of the nutrients and salts included in the simulation, which is of benefit to the decision making processes associated with the utilisation of manure and effluent.

The results presented from the database highlight the complexity of the relationships associated with the movement of nutrients and salts, as result of the utilisation of manure and effluent for crop production. Eutrophication of waterways caused by excessive nitrogen and phosphorus in runoff, increasing ground water salinity, nitrate contamination of ground water and the soil's nutritional status are some of the elements that need consideration, when investigating the sustainable utilisation of manure and effluent. Several important factors that effect the processes and interactions governing the transport of nutrients and salts within manure and effluent were identified. These were climate variation, cation exchange processes and N transformations.

This study focused on the sustainability of manure and effluent utilisation and several elements were shown to be essential components required for determining the sustainable utilisation of manure and effluent. These elements included adaptive management that is responsive to changes in the status of the system, as signalled by strategically monitoring the key variables and processes of the system. The monitoring information must be seen as a valuable asset and be used as input to a model that can regularly predict the medium-term (10-15 years) benefits and adverse affects of the current operation. That is, the data should provide a dynamic measure of the sustainability of the system.

Establishing a mass balance of the nutrient and salt fluxes in a feedlot was identified as being crucial to understanding sustainability issues. The manure and effluent utilisation area is a stochastic system and therefore a Monte Carlo simulation model was developed and used to enhance the current knowledge of the nutrient and salt fluxes. Inputs to this model were the probability distributions of the collected data and the output are various cumulative probability distributions, used to assess the behaviour of the nutrients in each of the output pathways in the feedlot utilisation area. Use of the EMU model can lead to better timing and application rates of the inputs (manure and effluent) and provides valuable information for determining an optimum management regime.

Models that simulate soil-water-plant system processes are plentiful and range in complexities. Some complex models represent a very small part of the system, and other models take a more holistic approach and aim at an understanding of the overall system. The modelling approach taken in this project is a compartmentalised one and is of the second type. The objective of the model was to assist the decision making process with both an environmental and production focus (Iskander 1981). Further developments of the EMU model should define an ideal manure and effluent application regime for maximum yields and nil environmental impact. The outputs from this ideal system can be used to compare with the outputs from the "real" system to provide ongoing production and environmental indices.

It was found that the EMU model required the integration of stochastic, deterministic and empirical components to simulate the output pathways. Simple representation of the fundamental variability of the system was obtained by viewing the output data from different viewpoints, that is, cumulative density functions of losses through runoff and drainage, average losses in each month of the year and total losses over a 6 year simulation. A subjective assessment was required to predict the optimal rate for both the production and environmental systems.

9.2 Recommendations

To understand all the processes and interactions that are important for the sustainability of the system, a model should incorporate the nutrient balance of the whole feedlot. The development of a decision support system would be a logical follow on from the current version of the EMU model. Incorporated with the Monte Carlo simulation, a decision support system would provide the basis for defining strategies to achieve the required nutrient balances.

Best management practices are needed to maximise the benefit obtained from the utilisation of manure and effluent and to ensure that the environmental and ecological equilibrium of the system is not degraded. A new equilibrium may occur as a result of utilising the resource, but it should be recognised that the new equilibrium position could be advantageous. However, any change in the equilibrium of one system will likely effect the equilibrium of another and this follow-on effect requires close attention. The equilibrium of the Na, K, Ca and Mg in the soil was shown to change in a 15 year simulation, using the current practices at the Tullimba feedlot.

Incorporating the effects of manure and effluent additions on aluminium concentrations and the consequent effects on pH should be included in further developments of the EMU model. The inclusion of soil structure as a function of manure additions, and the effects that this has on the water holding characteristics of the soil is also an important component that should be included in future versions of the model. Modelling the utilisation area also highlighted the need to address the Na concentration in the effluent before it is applied as an irrigation source. Developing methods that remove Na in an interim system were identified as an important research area.

The intensive monitoring conducted at Tullimba and other feedlots as part of the research into the sustainability of feedlots and the use of the monitoring data in a simulation model has identified important environmental indicators for the quantification of sustainability. The importance of cation concentration in the soil solution was highlighted as one area where data is lacking. However, methods are required for obtaining these, and other important data that are key indicators, in a way that is economical, easy to implement and interpret and timely in the commercial operation of a feedlot.

There is a need for a coordinated research, development and assessment plan in terms of understanding the impacts from the utilisation of manure and effluent (USDA & US EPA 1998). The database and simulation model outlined in this thesis provides a tool for the basis of developing such plans by providing a method to evaluate better manure management strategies before setting up expensive research plots.

The EMU model developed within this research has several benefits and with further additions and refinements it will be a useful tool for the management of a feedlot. Investigation of the effects of the feedlot on the air environment would require a module that explores the emissions of NOx and methane, which could be easily incorporated into the current EMU model. The EMU model could also be used as an education tool in addressing conservation, regulatory, production needs and the effects of climate change. Further developments of the environmental monitoring database and simulation tool should be geared towards making it available on the web and written in HTML so that it can be run on all computer operating systems.

It is important for the Australian Cattle feedlot industry to apply the latest technologies in the management of their enterprise and to be pro-active in adopting research findings. This will be made easier with tools that are user-friendly and scientifically based. The continued development of the EMU model in a systems framework will enhance the current understanding of the sustainable utilisation of manure and effluent, as the tool becomes more sophisticated.