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Appendix A. Sample Collection and Handling

A.1 Defining Proper Sample Collection and Handling

Early in the development of the Environmental Monitoring Database (EMD) it became apparent that the greatest problem with the collection, collation and interpretation of data was that proper sample collection, preparation and testing protocols needed to be established. Most error in environmental monitoring is induced in the field, or at the time of transfer of the sample to the lab.

Gaunt *et al.* (1997) state that a key issue for database construction is determining the most appropriate frequency for data collection to enable the detection of changes in time and achieving consistency of sample location and sample date. The following sections define the methods that have been adopted and some of the reasons why a particular protocol is used. Some of the following information on soil and plant sampling, preparation and testing has been drawn directly from Lisle and Blair (1996) and Lott *et al.* (1996).

A.1.1 Soils

A soil testing program involves:

- soil sampling;
- laboratory analyses;
- correlation between analysis and yield response;
- interpretation and recommendations; and
- putting information to use.

When considering the chemistry of the soil, there are three important components in the soil, which are shown in Figure A.1. The available component is reasonably mobile and will move in water passing through the soil lattice. The exchangeable component includes the available component and also the ions that are attached to 'exchange' sites on organic and clay particles. This exchangeable component gives a good indication of the proportion of the pool that is accessible to plants. The total component includes the available and exchangeable ions and also the elements that are tightly bound in organic matter, and inorganic compounds.

Most soil chemistry tests for exchangeable ions attempt to emulate the interaction between the plant and the soil. An example of this is the use of DTPA for the extraction of cations from soil. It is a chelating agent that mimics the removal of ions from the exchange sites in a similar manner to roots.

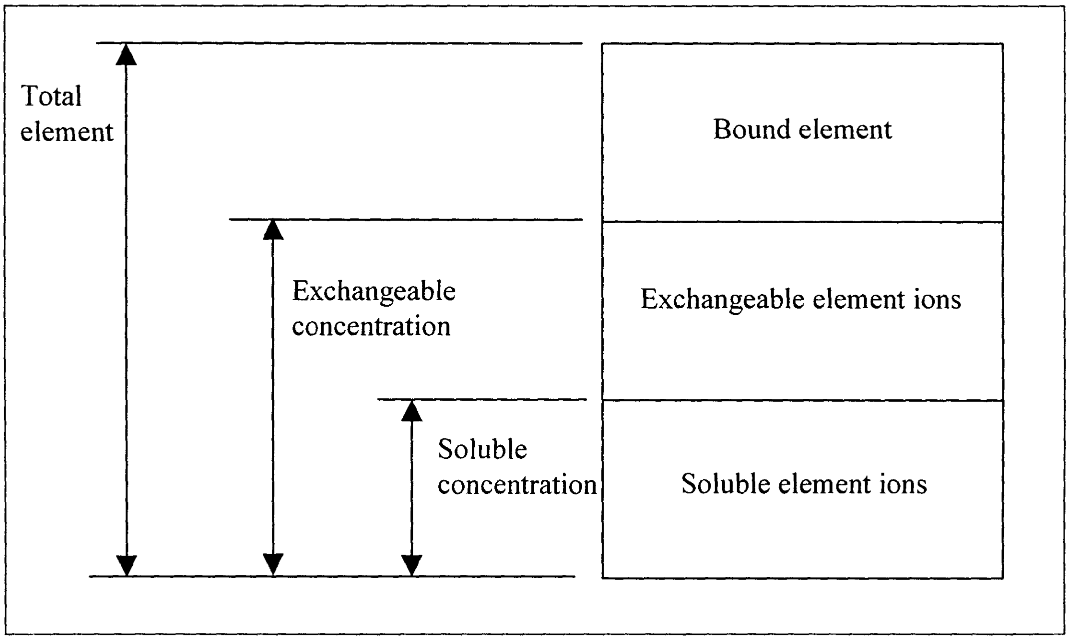

Figure A.1. Components of the Soil Solution

Soil sampling and testing needs to focus on components that yield meaningful data for environmental and production purposes. Techniques used should allow the soil chemistry and indicators of sustainability to be tracked through time and minimise the variation in the results. Variations in soil tests are due to three sources, which are outlined below.

1. Spatial variation, due to natural variation such as topsoil depth, uneven return of dung and urine, uneven fertiliser topdressing, differences in soil properties, etc.
2. Temporal variation, due to changes in soil moisture, temperature and, hence, biological activity, and the time since the last fertiliser application.
3. Laboratory errors which are generally small (<1%).

Soil properties often vary markedly over short distances and with depth, and different properties vary to different extents. The main aim in sampling is that the sample be representative of the soil in the area being sampled, so sampling techniques must minimise these variations. However, often results from soil sampling tests are variable and one way to express this variation is as a percentage error. In a New Zealand study (13 sites over 3 years), the percentage errors associated with the various soil tests are presented in Table A-1 (Edmeades 1986). The largest errors were found in the S, P and K tests, reflecting uneven return of dung and urine on grazed pastures, and variable S mineralisation from the organic matter.

Table A-1. Percentage errors associated with soil tests (Edmeades 1986)

Soil test	**Error (%)**
pH	2-5
Ca	10-15
K	20-30
Mg	10-15
Olsen P	15-20
SO_4-S	20-45

There are a number of sampling techniques and one for the collection of soil samples for environmental monitoring is briefly described in the NSW Feedlot Manual (NSW Agriculture 1995). This method requires surface samples to be collected in a Z pattern across a paddock. Figure A.2 shows the variations in phosphorus across a 10 ha paddock at the Tullimba feedlot, using a grid sampling technique. Given the amount of variation shown in Figure A.2, two slightly different Z sampling patterns would result in two completely different results and erroneous information.

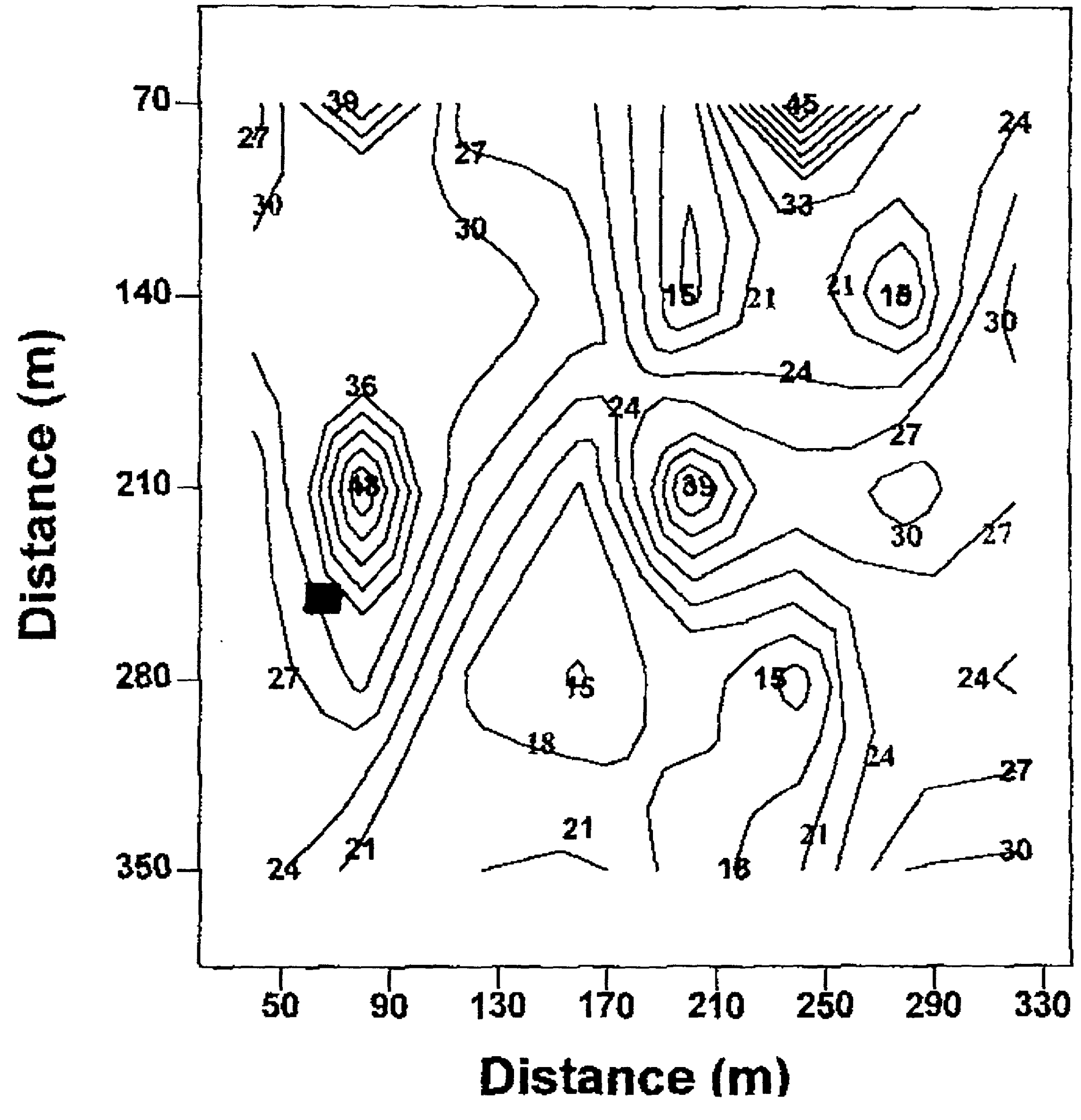

Figure A.2. Soil Chemistry of a 10 ha Paddock at the Tullimba Feedlot as Determined Using Grid Sampling

The NSW guidelines (1995) for cattle feedlots states that for 'composite' samples 30 to 40 cores, collected along a Z pattern are required for a 10 ha paddock. However to obtain statistically sound data, Friesen and Blair (1984) required 960 random samples to be collected for a 10 ha paddock. An alternative approach is to cluster sample at a 'reference site or monitor plot', which requires less samples and provides a better quality data set for the determination of crop fertiliser requirements (Friesen & Blair 1984). A response site or monitor plot is a small site of approximately 20 m diameter from where all samples are collected. This sampling technique lends itself to environmental monitoring because it provides reliable data that more accurately measures change in the environment. Therefore, the recommended practice is to use monitor plot sampling and sample from the same sites regularly over time (Friesen & Blair 1984; Lott *et al.* 1996). Twenty-five samples are taken from these monitoring sites and bulked for analysis.

There are simple requirements for sample collection, including an area that is homogeneous as possible, with different areas being separated on the basis of soil type, topography, crop or pasture growth and management history. Monitoring sites are established within each homogeneous sample area. Where sampling is going to continue, it has been argued that these monitoring plots should provide more reasonable estimates of the soil chemistry over time (Friesen & Blair 1984).

Monitoring plots should be located at representative sites across the paddock, avoiding sheep camps, wet areas, trees, timber burns, old fence lines, etc. When sampling, atypical sites should be avoided such as dung or urine patches, paths, waterlogged areas (unless these are the main interest), minor water courses or irrigation channels, tree stumps or their ash residue after burning, fertiliser dumps, and even fertiliser granules, where recently applied. Monitor plots should not be located anywhere near soil investigation pits or at the top or toe of a slope but rather mid slope and way from any drainage lines. Typically it is the site that is recognised by the farm manager as an "average" area within a paddock which provides the best location.

The depth of sampling depends largely on the agricultural system. For pastures, samples are usually taken to 7.5 or 10cm, for crops to 10 or 15cm, and for deeper-rooted tree crops, samples to 1m may be required. Separate samples should be taken from different depths, particularly for deeper samples or specific soil characteristics such as salinity or certain physical characteristics. This sampling can be done on the basis of fixed intervals (often smaller intervals are sampled near the surface) or, if possible, on the basis of soil horizons.

For production purposes, surface and other depths are sampled within the root zone. Typically, soil chemical analyses indicate the amount of an element that is available to the plant (e.g. exchangeable calcium), however, environmentally the interest is in the component which moves out of the system and into the environment. Therefore, the tests for plant nutrient/salt availability may not be the most suitable, as there is a need to test for the mobile and soluble ions, such as nitrate, ortho-phosphate and the cations. In particular the area below the root zone is of interest. Therefore soil in the root zone and below should be sampled with the tests required for each sample not necessarily being the same.

The NSW guidelines (1995) state that for 'profile' samples 5 cores need to be collected across a 10 ha paddock (3 for < 10 ha) and that these should be bulked together. Results from the research program at the Tullimba feedlot show that when using these techniques the variation in data from each sampling is greater than the variation between sampling times and as such these data do not provide an accurate measure of change in the environment. This is shown in Figure A.3 for data collected from the Tullimba feedlot. It is clear that the error associated with this type of sampling is significant, with no statistical difference between the values for the before and after TP concentrations.

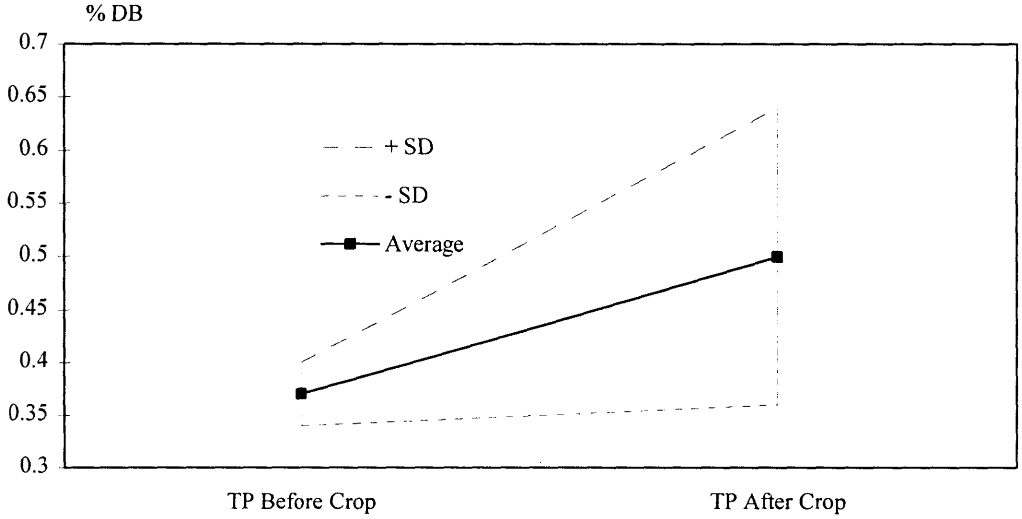

Figure A.3. Total Phosphorus in the Surface Soil Before and After Crop Using 3 Cores per 8 Hectares

Timing of soil sampling is important, as temperature, moisture, crop growth and crop residue levels will all affect soil characteristics, although different characteristics will be affected to varying degrees. The result is that soil test levels will vary over time. Soil sampling should also be appropriately timed, which is dependent on the characteristics being measured and the reason for the sampling. For most annual crops, where fertiliser and other management strategies are being planned, samples are normally taken before land preparation for sowing. For pastures, an appropriate growth phase/soil organic matter turnover phase, such as the rapid growth and organic matter turnover period in spring, is usually selected. In either case, if soils are being monitored repeatedly, it is important that the samples are taken at the same time each year. To determine the appropriate application rates of manure, effluent and inorganic fertiliser, soils should be tested prior to application.

The greatest hazard to the environment occurs when fertilisers have been applied and the soil moisture profile is full. As a full soil profile heightens the potential for significant losses in runoff and leachate, monitoring of ground water before and after the application of fertilisers will therefore provide an indication of any leaching of soil nutrients. Typically, soil sampling is not undertaken at this time because of the volatile chemistry of the soil and the lack of reliability in the test results due to chemical change.

For annual soil sampling, soil is collected after the first cultivation following harvest. At this time nutrient, salt and moisture have been stripped from the soil solution by the plant and an estimate for the next season's crop can be made. Unfortunately, considerable mineralisation can occur between this time and the subsequent crop sowing and this is not accounted for in recommendations for application rates.

The continued maintenance or improvement of soil health is paramount to the realisation of maximum crop production. If soil health declines, so does production rates, nutrient removal rates and economic returns from the crop. This decline will result in increased losses of nutrient and salt to the environment. Clearly, soil structure is one of the indicators of sustainability. A decline in soil structure is indicative of land degradation and harm being caused to the environment.

Soil structure can be monitored using physical tests for permeability or chemical tests on the exchangeable cations. Changes in the percentages of exchangeable cations will indicate changes in soil structure. For example, a steadily increasing percentage of sodium and decreasing proportion of calcium and magnesium indicates the soil is likely to be becoming more dispersive, have lower permeability, and reduced soil water storage. This accumulation of sodium ions can be readily described by the measurement of Exchangeable Sodium Percentage (ESP) in the soil.

There are many continuous chemical and biological interactions and transformations that occur in the soil profile. Even a very complex monitoring program could not provide enough information to be able predict, with complete confidence, the fate of the elements in the soil over a period of time. However suitable mathematical models can assist in this endeavour (Iskander 1981).

A.1.2 Surface Water

In agricultural situations, the quality of surface waters has historically been tested with reference to its use as an input for stock water or an irrigation source for a particular crop and soil. Analyses gives an indication of the management that may be necessary to control or compensate for a water quality related problem (Ayers & Wescot, 1989). The analyses undertaken to determine the suitability of a water as an input include (Ayers & Wescot, 1989):

- EC - a measure of the total salts present;
- total concentrations of nitrogen, phosphorus, sodium, calcium, magnesium, chlorides, sulfates; and
- bicarbonates.

An environmental monitoring program, however, requires a wider perspective that encompasses not only the production system, but also considers the effects of a nutrient load on external systems. This requires analyses to be broadened to include indications of nutrient enrichment of water bodies with phosphorus and nitrogen in particular.

Phosphorus and nitrogen are the limiting growth factor in many aquatic systems and therefore their abundance will be the cause of eutrophication (Emsley & Hall 1976). As phosphorus can be present in soluble and insoluble forms, total phosphorus and soluble ortho-phosphate should be measured (Rayment & Higginson 1992). In most natural uncontaminated Australian water bodies, nitrogen concentrations are generally low (typically < 0.1 mg N/L), therefore an increase in nitrogen can be an important indicator of eutrophic waters (Rayment & Higginson 1992). The nitrogen species of importance are nitrate, nitrite and ammonium ions.

Other parameters that should be measured in surface waters that may be affected by a system utilising the manure and effluent from an intensive livestock operation include (Rayment & Higginson 1992):

- suspended solids;
- pH; and
- alkalinity.

Suspended solids reduce light penetration, which in turn reduces photosynthetic activity of phytoplankton, algae, and macrophytes, resulting in a reduced food supply for many invertebrates. This reduced food supply can reduce fish populations (NCSU 1996). Changes in pH result in different chemical reactions occurring in the water body. For example, a reduction in pH may allow the release of toxic metals that would otherwise be sorbed to sediment and essentially removed from the water system (NCSU 1996). pH is a measure of the hydrogen ion concentration and as pH decreases, the concentration of hydrogen increases and the metal cations experience greater competition from the hydrogen ions for binding sites (NCSU 1996).

Obtaining representative samples from surface waters can be difficult, particularly when the body of water is spatially and temporally heterogeneous. Confidence in the results of water chemical analysis is also dependent on the integrity of the samples taken (Rayment & Higginson 1992). The techniques and procedures adopted to obtain, preserve, transport and label water samples are important variables in any environmental monitoring program.

NSW EPA (1998) state that for land utilisation areas receiving treated wastes, such as sewage irrigation areas, the factors that need to be considered in determining the frequency of monitoring of surface water include the proximity of the water body and the parameters to be measured. The NSW EPA (1998) recommend that surface waters be sampled prior to irrigation with effluent and following storm events. This sampling should include points both upstream and downstream of the utilisation area.

Losses to surface water from feedlots can occur through holding pond and terminal system spills (i.e. losses from the effluent irrigation system) resulting from episodic rainfall events producing runoff that exceed the design capacity of the storage facility. Therefore, surface water samples should be collected from the water body before the irrigation season under reasonably static low flow conditions. If the holding pond or terminal pond system spills due to major storm events then samples of the spill water and creek water above and below the feedlot should be collected.

If baseline data are not available, then sampling frequency should be greater in the earlier stages of operation. The baseline surface water quality will vary markedly, which is supported by similar variations in ground water quality and surface water data collected below the Tullimba feedlot (see Chapter 4).

A.1.3 Ground Water

An increase in the level of a particular ion in ground water suggests that a significant accession may have occurred. Accessions to ground water typically occur after prolonged rainfall and as such occur in every type of ecosystem.

Degradation of ground water limits its future use as a domestic or stock water supply. If this degraded ground water supplies the creek base flow, then the surface waters can also be degraded through salinity or eutrophication. It is extremely difficult to recover excess nutrients and salts from ground water once they are present. Ideally, the likelihood of a 'problem' (accession of nutrient or salt) should have been picked up in the deep soil-sampling programme as an excess of available ions before they were leached in deep drainage water. Good monitoring programs should aim to achieve this level of investigation.

Losses of soil water to ground water are affected by the volumetric rate of deep drainage. This drainage rate is regulated by the hydraulic conductivity of the soil, which is influenced by soil type and its chemistry. The quantity of nutrient and salt loss to the ground water is also influenced by the concentration of available nutrient and salt below the root zone, where excesses should not be allowed to accumulate. This approach presents a real difficulty because historically salt build up in soils have been managed by the addition of a leachate fraction and consequently allowing loss of salts to ground waters.

The most important variables in the monitoring of ground water are the concentration of the ions and the volume of the inflow (accession), as these dictate the gross amount of nutrient and salt loss to the ground water. Typically, this is measured through a change in the standing water level in the piezometer or monitoring bore. Key environmental indicators in ground waters are nitrate, ortho-phosphate, possibly bacteria populations and salinity.

Research at the Tullimba feedlot has shown considerable variability in water quality attributes in the ground water, which is accentuated in the irrigation area. The CRC research project on environmental monitoring indicates that of the 32 piezometers located in and around the Tullimba feedlot, about 10 could provide enough surveillance points. However, samples need to be collected regularly and at the Tullimba feedlot, collection at a frequency less than once per quarter is likely to provide useless data. Ideally the timing of the collection should be before and after a rainfall event, which will give an indication of the inflow and therefore the gross amount of nutrient and salt.

A.1.4 Crop

The use of plant analysis should be carried out in conjunction with information from soil tests, field and glasshouse experiments, foliar symptoms and background information in making a diagnosis of a particular nutrient stress. It is important that the reasons for taking particular plant samples for analysis are appreciated, as they effect the way the samples are taken. In many respects, the principles behind the collecting, handling and analysing of samples are the same irrespective of the aims of the sampling. However, unless due care is taken with all these steps, the results will be unreliable and may result in misleading interpretations (Lisle and Blair 1996).

Plant analysis is carried out for three basic reasons (Lisle and Blair 1996):

(a) diagnostic testing - trouble-shooting by testing poor and healthy crop;

(b) monitoring - to assess the adequacy of current fertiliser practice and related management practices (i.e. irrigated cotton testing petiole NO3- levels); and

(c) prognostic testing - to determine whether a crop is going to run into nutrient deficiency, to predict behaviour in storage, or to predict likely deficiencies in succeeding crops by grain analysis.

The concept of critical nutrient concentration forms the basis of most methods that use plant analysis to assess plant nutrient status. In general, it refers to the concentrations around the 90% of maximum yield. This should not be a single value but a range of nutrient concentrations above which the plant is amply supplied with nutrients, and below which the plant is deficient (Reuter & Robinson 1986).

There is considerable diversity in critical concentrations among different species. When plants are considered at a similar physiological age, it becomes possible to construct major groupings of related plant species. When one looks for differences in critical concentrations between cultivars of the one species, it is found that there are minimal differences in wheat for NO_3-N (Papastylianou & Puckridge, 1981) or for Cu in cereals (Nambiar 1976). It should be realised that although two cultivars or species may have similar critical concentrations for an element in a particular plant part, they may have different external requirements for that element due to the differences in their ability to explore for, absorb and transport nutrients (Lisle and Blair 1996).

Growth and development cause marked changes in nutrient concentrations in plants as the growing season progresses. Generally, the concentration of N, P and K decrease with age, whereas the concentration of Ca, Mg, Mn and B often increase. Young leaves therefore show relatively high contents of N, P and K whilst the older leaves can have a high level of Ca. Changes in the critical concentrations, over time, for the whole shoot of wheat (90% maximum yield), for N, P, and K are given in Table A-2.

Table A-2. Changes in Critical Nutrient Concentration with Age in Wheat (Reuter & Robinson 1986)

	Critical Concentration (whole Shoot) (%)		
Stage of growth	**N**	**P**	**K**
Very early tillering	5.8	0.62	4.1
Tillers formed	5.0	0.56	3.2
Leaf sheath length	4.6	0.35	
Leaf sheath erect	3.9	0.23	
1st node of visible stem	3.4		
2nd node of visible stem	3.0		2.0
Last leaf visible	2.8		
Ligule of last leaf visible	2.3		
Booting	1.9		1.5
Heading	1.7	0.12	
Grainfill	1.4		0.9

The uptake of a particular nutrient can be increased or decreased by the presence of other nutrients in the rhizosphere, without necessarily resulting in changes in dry weight. Thus, the level of one nutrient can influence the concentration of another nutrient. The effect of changing one nutrient in the soil may therefore change the concentration in plant tissue of another. There are considerable changes in the soil for Na, Cl and K at the Tullimba feedlot, which indicates further analyses of the crop data are required to compare concentrations in the plant tissue with those that would be expected. Antagonistic interactions occur between K and Mg, K and Ca, Ca and Mg, Fe and Mn, Cu and Fe, P and Zn, P and Fe, while synergistic variations include P and Mo, $N0_3$ and Ca. One documented example is the 'sparing effect' of Na on K. In *Chloris gayana*, critical K concentration in shoots can be reduced from 2.1% to 0.4% by the addition of Na (Lisle and Blair 1996).

A.1.4.1 Limitations of Plant Analysis

There are several limitations to plant analysis. Five of these limitations are listed below.

1. Plant analysis for a particular nutrient is only meaningful if that nutrient is the only limiting factor to plant growth. If it is not the limiting factor, then the relationship between nutrient concentration and plant growth has no useful meaning.
2. Plant analyses cannot indicate the fertiliser rate that should be applied to correct the deficiency. Such information requires soil tests and field experiments to be conducted.
3. Plant analyses cannot determine how the nutrient disorder arose, such as a lime-induced zinc deficiency.

4. Plant analyses indicate the nutrient status at the time of sampling and limited information is available for assessing the nutrient status later in the season.
5. Plant analyses cannot tell the magnitude of the response attained by improving nutrient concentrations in the plant. In the field, plant responses are subject to all the vagaries of the environment and are likely to differ considerably from those suggested by an 'ideal' relationship between yield and nutrient concentration.

A.1.4.2 Published Critical Concentration Data - the Key to Plant Analysis

Interpretation of plant analyses data requires reference data. Various texts contain the various nutrient concentration ranges for different crops and specific plant parts, sampled at certain stages of crop development (see Chapman 1966; Reuter & Robinson 1986). An example is given in Table A-3.

Table A-3. Critical Values Used to Classify a Plant Analysis of Corn Ear Leaf (Reuter & Robinson 1986)

Element	Deficient	Low	Sufficient	High	Excess
N	2.45	2.46-2.75	2.76-3.50	3.51-3.75	3.75
P	0.15	0.16-0.24	0.25-0.40	0.41-0.50	0.50
K	1.25	1.26-1.70,	1.71-2.25	2.26-2.50	2.50
Ca	0.10	0.11-0.20	0.21-0.50	0.51-0.90	0.90
Mg	0.10	0.11-0.20	0.21-0.40	0.41-0.55	0.55
ppm					
Mn	15	16-19	20-150	151-200	200
Fe	10	10-20	21-250	251-350	350
B	2	3-5	6- 25	26- 35	35
Cu	2	3-5	6- 20	20- 50	50
Zn	10	11-20	20- 70	71-100	100
Mo	Always sufficient				
Al	---	---	200	200-401	400

* For leaf sampled when in initial silk

In an environmental monitoring context, plant analyses provides information on the amount of a particular parameter that is being extracted from the system. This information is particularly important when modelling the cycling of nutrients in the system.

A.1.5 Effluent

There is considerable variation in the quality of effluent over time. This variation is a function of rainfall, evaporation, ration, slope of the feedlot pens and the drainage system that drains the effluent to the holding ponds. To understand the variations, data is required and then the database can be used to investigate these variations and other relationships that exist in the datasets. For example, the relationships between EC and the concentration of cations.

A.1.6 Manure

The reasons for analysing the manure are similar to those for effluent - i.e. knowing the inputs to the system. However, the characteristics of manure change considerably over time, especially when it is stockpiled. These changes are important to monitor to try to establish a relationship between the manure characteristics and the time period the manure has been stockpiled. Once the manure has been incorporated into the soil, considerable mineralisation of the organic matter to an inorganic form available for plants continues for considerable time (in the order of years).

A.2 Storage and Treatment of Environmental Monitoring Samples

Proper storage and treatment of samples is critical to obtaining reliable analytical results and thus meaningful monitoring data. Improper sample collection, handling and treatment are by far the greatest source of error in data. This section has been drawn from Lott *et al.* (1997).

Soil samples are usually collected using corers (tubes), augers or spades/trowels. To avoid contamination, the sampling equipment must be clean, and the samples should be placed in clean containers. If it is necessary for the samples to be kept for a short time before dispatching, the bags should be left open to prevent sweating by the samples. When tests for micronutrients are likely to be included in the chemical analysis, uncontaminated, heavy duty, polyethylene bags are preferred. Handling of the samples should be avoided or kept to a minimum. Samples should be forwarded to the laboratory as soon as possible, as changes in soil pH, available N and exchangeable Al during storage can occur in the soil samples (Singh & Kenehiro 1970). If the soil is to be tested for available nitrate, then the sample is best air-dried at ambient temperature or kept cool prior to analyses.

Many analyses are not significantly affected by complete air drying for storage purposes, however there are exceptions. Some analyses, such as exchangeable ferrous iron and manganese, exchangeable potassium, acid extractable phosphorus and nitrate nitrogen must be carried out on moist samples immediately after collection. If these samples need to be stored, it is best achieved by freezing, or freeze-drying.

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Appendix B. Review of Modelling Literature

The trend of simulating agricultural systems did not begin in earnest until the 1970s and this trend is continuing strongly today (Stockle 1996b). The first attempts at simulating crop growth used simple empirical relationships that related yield to climatic variables (Mahdian & Gallichand 1995). The latest generation of agro-ecosystem models is highly sophisticated and based on soil water balance and nutrient cycling (Mahdian & Gallichand 1995). See Sadler (1983) for a history of crop model developments up until 1983.

B.1 Types of Models Considered

There are a multitude of approaches that can be adopted in the application of a simulation model to study the utilisation of manure and effluent by an agricultural production system. The many adjectives to describe models include deterministic, empirical, stochastic, mechanistic, steady state, dynamic, equilibrium, rate, analytic, numeric, functional, conceptual and process driven (Gaunt *et al.* 1997; Grayson & Chiew 1994; Iskander 1981). The purpose of the model, its complexity, flexibility and transferability are components that can be used to assist in identifying the label to describe the model type (Gaunt *et al.* 1997).

A mechanistic model attempts to describe the most fundamental mechanisms of the process, whereas the aim of a functional model, which employs a holistic approach, is to provide a general description of the overall process (Gaunt *et al.* 1997). Empirical models give minimal consideration to the physical relationships between parameters and processes and use statistically derived relationships (Grayson & Chiew 1994). Deterministic models compute outputs as a function of the inputs to the system, that is, a cause-and-effect relationship is assumed (Iskander 1981). In contrast, a stochastic model computes the outcome with less than unit probability, that is, the outcome is not exactly known. Deterministic models are more common, and they comprise a range of simple algebraic and ordinary differential equations to non-linear partial differential equations that have to be solved by numeric approximations (Iskander 1981).

Conceptual models usually represent the catchment as a number of interconnected storages, with mathematical functions to describe the movement of water (and other fluxes) into, between, and out of them (Grayson & Chiew 1994). These models generally use empirical equations and 'effective' parameters to describe the physical processes (Grayson & Chiew 1994). When single parameters are used to represent the entire catchment in a conceptual model, they are known as lumped parameter models.

A lumped parameter model is concerned with the relationship between inputs and outputs, as a function of time, and is not concerned with their distribution in space. A distributed lumped parameter model takes into consideration the spatial characteristics of the system (Iskander 1981). Spatial heterogeneity can be accounted for by applying conceptual and distributed process models to individual sub-areas with simple conceptual models usually requiring less than 8 parameters to be calibrated (Grayson & Chiew 1994).

Physically based hydrological models have a numerical solution based on the Richard's and St. Venant equations or simplifications of these equations (Grayson & Nathan 1993). The problem is broken down into smaller and smaller elements and the individual elemental outputs are pieced together to form the solution to the overall problem (Grayson & Nathan 1993).

Grayson and Nathan (1993) urge caution when using so call physically based models in engineering hydrology. The algorithms used in these complex models are generally formulated at very different temporal and spatial scales to those to which the model is applied (Grayson & Nathan 1993). The algorithms used are generally based on an understanding of the processes that occur at the scale of a laboratory soil column, and not on research catchments where there is great variation in these values (Grayson & Nathan 1993). If the model is applied at these different scales it is no longer physically based, but rather an over-parameterised empirical model (Grayson & Nathan 1993).

When applying "fundamental laws", such as Darcy's law and Fick's law to a natural heterogeneous system, it should be remembered that they are only rough approximations of what is occurring, and the one and only complete and true model of a natural system is the system itself (Iskander 1981). This needs to be balanced with the level of complexity incorporated into a model. The complexity of the modelling project should be of sufficient level to solve the problem and no more, and should have the inherent characteristics of the system built into the model (Grayson & Chiew 1994; Hamer *et al.* 1987).

Process models use fundamental equations, such as Richard's equation, to represent physical processes (Grayson & Chiew 1994) and provide estimates of runoff and sediment transport as well as infiltration using reasonable time steps (Eigenberg *et al.* 1995). The parameters used in process models have physical meaning, such as hydraulic conductivity, porosity, leaf area index (Grayson & Chiew 1994). Distributed process models subdivide the area under investigation into many small areas using, for example, finite-difference grids. These models are often applied to small experimental plots and use partial differential equations and equations for continuity of surface and soil water flow (Grayson & Chiew 1994). Process models are best suited to describe the dynamics of plant growth. Time and weather data are inputs to process models and they relate the plant physiology to nutrient uptake (Eigenberg *et al.* 1995).

Research models generally have several limitations that do not allow their wide spread use. Firstly, there is usually an expectation that new data will be required by research models for sensible execution (Grayson & Chiew 1994). Research models are also in a state of constant development, often in conjunction with a wider program of research and field work and are often only used by a few researchers (Grayson & Chiew 1994). The types of models commonly used in research are distributed conceptual or process based models (Grayson & Chiew 1994). Research models are usually flexible, though more often than not are difficult to use and poorly documented (Grayson & Chiew 1994).

A reason why models that are developed to provide better management of a particular system are not in genuine use, is that they were produced without proper consideration of the end-users need (Grayson & Chiew 1994). The model outlined in this study was developed with a view to using monitoring data collected as part of the normal monitoring requirements of a feedlot. The use of monitoring data as input is to overcome the problem of transferring an agro-ecosystem model developed at the laboratory scale to the field scale (Gaunt *et al.* 1997; Mirschel *et al.* 1997).

The use of hydrologic models has traditionally been to predict the temporal and spatial behaviour of surface water, ground water, sediment, salts and other elements (Grayson & Nathan 1993). Hydrological models have also been used to investigate the impacts from various management practices (Grayson & Nathan 1993). These models require interfaces that are simple to use and understand (Grayson & Chiew 1994).

B.2 Range of Models Available

There is a multitude of models available for agro-ecosystem research from various research centres around the world. The CERES (Crop Environment REsearch Synthesis) series of models are the most widely used in research and have been developed for maize, barely, rice, sorghum, and wheat (Mahdian & Gallichand 1995). The variety of other models that are available include (The United States Salinity Laboratory 1998):

- statistical software packages for analysing field scale data - ESAP, GOOPACK;
- models to simulate water, heat and solute movement in porous medium, these include several versions of HDRUS, SWMS-2D and 3D, TETRANS;
- models to analyse and predict the hydraulic properties of soils –RETC and UNSODA;
- models that concentrate on salt affected agro-ecosystems – SALT; and
- predictive simulation models based on process orientated relationships, for example SOILCO2.

In the USDA Agricultural Research Service's 1999 Annual Performance plan (Agricultural Research Service 1998) one of the performance goals was to demonstrate and transfer to users, computer-based simulation models and decision-support systems. To this end a model has been developed to evaluate management practices in swine production systems. The USDA plans to make this model available on the Internet, and thus provide information that producers can use to reduce production costs and protect the environment (Agricultural Research Service 1998). The use of the Internet in this way is promising and will provide much greater access to models for the agricultural community. For a model to be successful, it should be simple and require minimal input data.

Maul and Koch (1996) recognise the need for clear interfaces in the models used by different researchers and developers and used an object-orientated method in their development of SIMSET. An essential part of the method was the definition of attributes and decision variables that influence objects in other parts of the system. Maul and Koch (1996) broke down the different procedures for pig fattening into five major elements and expressed each of the elements as equations. The five elements were animal growth, conversion of fodder into products, substance flows, manure behaviour, and costs of the different procedures, thus providing a holistic model of the system.

There are many models that can be used to determine the effect of agricultural management practices on water quality and various components of an agro-ecosystem. These are (National Water and Climate Center 1997; Reyes *et al.* 1994; Saleh *et al.* 1994): AGNPS (Agricultural Non-Point Source Pollution Model), GLEAMS (Ground water Loading Effects of Agricultural Management Systems), CREAMS (Chemical, Runoff, and Erosion from Agricultural Management Systems), EPIC (Erosion/Productivity Impact Calculator), NTRM (Nitrogen, Tillage, Residue Management Model). RZWQM (Root Zone Water Quality Model), SPAW (Soil - Plant - Air – Water), SWRRBWQ (Simulator for Water Resources in Rural Basins - Water Quality), WEPP (Water Erosion Prediction Project) and DRAINMOD.

Other models that include runoff components include HSPF (Hydrology Simulation Procedure - FORTRAN) and CANDY (Carbon and Nitrogen Dynamics). HSPF has a catchment perspective and was developed by the US Environmental Protection Agency to simulate watershed scale processes (National Water and Climate Center 1997). CANDY has a narrower spatial focus and simulates transport of water, long term changes of soil carbon content and short term nitrogen dynamics of various soils under different management conditions using a daily time step (Ramsbeck *et al.* 1997).

Some models, such as the SAFE (Simulating Acidification in Forested Ecosystems) and CropSyst models attempt to represent many processes and interactions of the whole system. SAFE is a conceptual model of a forest soil and includes a simplification of the following processes (Sverdrup *et al.* 1995):

1. deposition, leaching and accumulation of dissolved chemical elements;
2. chemical weathering reactions of soil minerals within the soil solution;
3. cation exchange reactions;
4. the net result of reactions of N-compounds, complete nitrification;
5. internal cycling of N and base cations in the canopy;
6. biological net uptake of base cations and nitrogen; and
7. solution equilibrium reactions involving CO_2, Al and organic acids.

The CropSyst model simulates the soil water budget, soil-plant nitrogen budget, crop phenology, crop canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and pesticide fate (Stockle 1996a). The management options that the user can manipulate include crop rotation, cultivar selection, irrigation, nitrogen fertilisation, pesticide applications, soil and irrigation water salinity, tillage operations, and residue management (Stockle 1996a). The area over which the model simulates crop growth is 1 m^2. Crop growth in CropSyst is a function of water, nitrogen, light, and temperature (Stockle 1996a).

MWASTE, POULIT and the Farm Nutrient Management Planning models are examples that focus on the fate of nutrients in manure. MWASTE evaluates coliform contamination in runoff from animal waste management systems (National Water and Climate Center 1997). The Farm Nutrient Management Planning model, which is a Pennsylvania State University computer program, uses on-farm data to recommend manure and nutrient application rates (National Water and Climate Center 1997). POULIT (Scott *et al.* in press) is a simulation module of the fate of nitrogen applied in poultry litter to tall fescue. The physical, chemical and biological processes of N transformation and transport are included in the model (Scott *et al.* in press).

There have been several models developed that investigate the decomposition of soil organic matter and nutrient cycling process (Syers & Craswell 1995) including the Rothamsted carbon model, CENTURY, NTRM, NCSOIL (Syers & Craswell 1995). The CENTURY model is a process model that simulates the dynamics of an agro-ecosystem with the objective being to analyse soil organic matter dynamics as a result of changes in management practices and climate. Monthly time steps are used and simulations of up to several thousands of years can be run to examine the flows of carbon, nitrogen and phosphorus (Register of Ecological Models 1998).

Input data required for the CENTURY model are the monthly mean maximum and minimum temperatures, precipitation, soil texture and depth, vegetation types and CO2 levels. Carbon and nitrogen fluxes, along with primary production and soil organic matter data are the outputs of the program. The program can be run using a DOS or Unix operating system on a regional scale with most executions at the 1m^2 resolution (Register of Ecological Models 1998).

The nitrogen model is the only model found written in hyper text markup language and can be run on any computer that has access to the Internet, regardless of the operating system (Greenwood *et al.* 1998). The model estimates the response of 24 different C3 crops (mostly vegetable) to the application of nitrogen fertiliser and the incorporation of crop residue as a function of time, soil type, cultural practice and climate. There are weather files with daily mean temperature, rainfall and potential evaporation for many different countries around the world, including Australia (capital city data). The weather files can be changed for regions that are not included. A potassium module is also included for some crops. The model is also available as a PC stand alone version (Greenwood *et al.* 1998).

There are several examples in the literature of decision support and management systems that offer promise at the farm level. An example is TALUTARK, which is a method of data acquisition and processing that provides a rational 'thinking-framework' for recognising and solving agro-ecosystem problems (Rutel 1997). Rimmington *et al.* (1988) report on the use of an expert knowledge software system for the building of crop water balance simulation models. This expert system was developed as a first step towards producing an "intelligent simulation package" (Rimmington *et al.* 1988). Attonaty et al. (1997) assert that their exploration support system, developed as a decision support model, plays the role of a pilot by simulating the technical decisions during the period of crop production, by linking state indicators of the system with executable actions.

B.3 Examples of the applications of selected models

Researchers have used models to try and understand the agricultural system and the effects different management practices have on the system for quite a long time in Australia. Fitzpatrick and Nix (1969) used a water balance accounting method to simulate the effects of the soil water regime on crop yields. The aim of this modelling exercise was to develop a methodology to quantitatively assess the suitability of a semi-arid region in central Queensland to a fallow-crop system (Fitzpatrick & Nix 1969). Various indices were developed of the crop-water environment using soil water simulations. These were used to analyse the effect of water stress at different stages of crop development and were found to be quite effective, considering the limited capacity of computers at that time.

Recent examples of applying models in Australia are given by Karm *et al.* (1995), who used historical daily rainfall and evaporation data in water budget models for the design of effluent irrigation schemes. In this model it was found that the annual water budget rather than a nutrient budget dictated the irrigation area requirements, except when the irrigation system was designed to rely upon the ability of the soil to remove phosphorus. In this case it was found that phosphorus was the variable that determined the area of land required for irrigation (Karm *et al.* 1995).

The SimSET model tracks information, environmental and economic flows of an agro-ecosystem (Ackermann & Schlauderer 1997; Maul & Koch 1996). A holistic approach is used to evaluate agricultural production by making visible the environmental load, consumption of resources and capital investments (Ackermann & Schlauderer 1997). However, the SimSET model is limited to investigating feeding up to slurry storage with slurry-housing systems in pig fattening the only system included. There are plans to extend the model to include slurry and solid manure field applications in the future (Ackermann & Schlauderer 1997; Maul & Koch 1996).

The SIMSET model can be used to combine multiple management and technical variations in the model and observe the reaction of the biological system. The environmental loads of the noxious gases related to production procedures are evaluated by calculated costs of environmental pollution (Ackermann & Schlauderer 1997; Maul & Koch 1996). To run the model, a reference variant is defined (e.g. the number of animals and design of their housing, feeding information, daily weight gains and slurry storage designs). The variant is then investigated by simulating the effects of different strategies for pollution control (Maul & Koch 1996), such as incorporation of a biofilter, acidification of slurry with lactic acid, using slurry covers of the slurry storage device and a combination of these factors (Ackermann & Schlauderer 1997). The example given in the paper by Ackermann and Schlauderer (1997) showed that the acidification of slurry with lactic acid was highly efficient in reducing emission of the noxious gases that are included in the model. However, the incorporation of these measures would not be financially viable under the existing conditions (Ackermann & Schlauderer 1997). The ultimate aim of SIMSET is provide sufficient data for complete substance flow management concepts (Maul & Koch 1996). Maul and Koch (1996) report that SIMSET showed normal management practices have significant effects on pollution.

B.4 Models Specific to Intensive Animal Feeding Operations

There are a variety of models that have been developed for designing feedlots, which cover different aspects of the system. There have been several physically based hydrological models developed to simulate runoff from cattle feedlot pens (Lott 1998; Watts & McKay 1986). The objective of these modelling exercises was to provide a tool for the innovative design of runoff control facilities (Watts & McKay 1986). However, the focus in recent times has been on the development of decision support system in the context of managing the intensive animal system.

B.4.1 Decision Support Systems

Lewis *et al.* (1997) describe a computer based decision support and analysis system. This system does not simulate the environment, but rather converts user input into an eco-rating through an audit of their management practices. Application rates and parameters that effect the fate and transport of environmental pollutants, together with simple heuristic models, are used to measure environmental performance (Lewis *et al.* 1997). This model has the ability to evaluate the environmental effects of intensive livestock husbandry but is orientated towards indoor production facilities, such as those used to raise pigs and poultry (Lewis *et al.* 1997).

MAP (Manure Application Planner) generates and evaluates the economic and environmental feasibility of manure applications using a linear programming approach (Schmitt *et al.* 1997). Linear programming has a proven optimisation routine for manure planning (Schmitt *et al.* 1997). Fertiliser replacement value, haulage and application costs are the economic variables included in MAP. Different nitrogen and phosphorus application rates are used to evaluate the environmental feasibility of a manure application regime and farm nutrient supply is calculated as a function of the amount of manure that is available for spreading on an annual basis (Schmitt *et al.* 1997).

Cros *et al.* (1997) outline a simulation model of a dairy farm rotational grazing system that couples the decision process with the biophysical system. This is similar to the grazing model developed by the EUNITA Working Group H (1997) where they considered a human and a biophysical dimension. The human dimension defined the objectives, motivation and behaviour of the farmer, while the biophysical dimension considers the interactions between the various biological and physical components (EUNITA Working Group H 1997). The strategy was to develop a conceptual model of a generalised grazing system and incorporate more specialised sub-models when required for specific situations (EUNITA Working Group H 1997). The biophysical system in the Cros *et al.* (1997) model is represented by empirical laws using a daily time step and includes the dynamics of several interactive subsystems. The driving variables for the biophysical system are climatic and the decision system relies on variables such as nitrogen levels, grazing and cutting operations etc. Different strategies are defined and simulations for various climatic conditions are run. If the outputs for this run meet the predefined objectives with sufficient certainty then the model suggests that an appropriate strategy for operating the rotational grazing system has been found. If this is not the case then the model is run again with a reformulated strategy (Cros et al. 1997).

ManureN also focuses on the nutrients contained in manure and allows the investigation of different management practices such as the time and frequency of different manure application rates (Sri Ranjan *et al.* 1995). The nitrogen distribution among the crop, ground water and soil is used to investigate the system as a result of these different management practices (Sri Ranjan *et al.* 1995). ManureN incorporates the main parameters that influence the rate of mineralisation of the nitrogen in manure and plant uptake of water and nutrients (Sri Ranjan *et al.* 1995) and is being used to evaluate the sustainability of irrigated agriculture in the Manitoba region of Canada (Sri Ranjan *et al.* 1995).

Of the models investigated that may be suitable, either their input data requirements or the cost in obtaining them have precluded from being used in this study. ManureN is probably the most suitable, but it has been developed for conditions in Canada and include the effects of frozen soil (Sri Ranjan *et al.* 1995). Even though irrigation is one of the variables that can be altered to observe the effects of different management practices, ManureN does not include irrigation with effluent, and is limited to a 5 year simulation (Sri Ranjan *et al.* 1995). Also required in the model to be used in this study is a method of incorporating the inherent variability of the system and in recent times there have been a few models of different parts of the agro-ecosystem using Monte Carlo simulation of the stochastic parameters.

B.5 The Use of Monte Carlo Techniques in Models of the Agro-ecosystem

Climate variability can have a more profound effect than changes in mean climate on agro-ecosystem variables, such as yields (Gaunt *et al.* 1997). Hamer *et al.* (1987) quantified the reliability of planting a wheat crop in any year and the likely yield of the crop by constructing yield probability distributions produced by simulation runs of a model of the cropping system in conjunction with long-term rainfall records. These simulations highlight the importance of capturing the variability in the weather by statistically generating climatic variables.

A dynamic, stochastic system must have an ability to continue into the future as one of the main criteria of sustainability (Hansen 1996). Hansen and Jones (1996) report on a study that investigated long-term sustainability of crop sequences using a simulation model with stochastic weather inputs. Trends and variability in yields, tenure arrangements, irrigation and rain, and variable costs, were investigated on a coastal rice farm located in Texas, USA. Variable costs, rice crop share and the absence of irrigation were found to significantly limit the ability of the farm to continue into the future.

Another study applied stochastic simulations to the EPIC (Erosion-productivity impact calculator) model and investigated the long-term impact of soil erosion on the productivity of crop rotations. The output from this study showed no negative trend in crop yields and the authors suggested this inferred sustainability (Hansen 1996). However this does not seem to be a sufficient criteria, as it does not include any external environmental affects.

EPIC, SUCROS and CropSyst are generic crop simulators that have been developed to include the capability of simulating different management options and predicting environmental outcomes (Stockle 1996b). The CropSyst model incorporates the production system and environmental impact by providing a tool to analytically study the effects of various management options on cropping systems and the environment (Stockle 1996a). Multiple cropping cycles for different crops can be simulated using a daily time step and a stochastic weather generator (Stockle 1996a), and the effects of applying different management practices can be investigated.

Another example of a stochastic model that considers many parts of the system includes the USDA's SWRRBWQ (Simulator for Water Resources in Rural Basins Water Quality) model. SWRRBWQ simulates hydrologic, sedimentation, and nutrient and pesticide transport processes, crop growth and reservoir storage in large, complex rural watersheds (Civil/Environmental Model Library 1993). A first-order Markov chain method is used to simulate rainfall. Temperature and solar radiation are generated from the normal distribution (Civil/Environmental Model Library 1993).

Several stochastic models developed recently, focus on the erosion processes of the system. PRORIL (Lewis *et al.* 1994a; Lewis *et al.* 1994b) treats rill density, fill flow rate and rill flow time as stochastic variables in simulating the erosion process and the EPIC model uses a simplified crop growth module to estimate erosion as affected by different cropping systems management (Stockle 1996b). WEPP (Water Erosion Prediction Project) (Tiscareno-Lopez *et al.* 1994) applies a Monte Carlo simulation and regression analysis to estimate the sensitivity of a complex, non-linear model of the erosion processes. Tiscareno-Lopez *et al.* (1994) found the sources of errors in their Monte Carlo simulation of the erosion processes came from errors in rainfall characteristics, errors in estimating the hydraulic conductivities, and errors in representing the antecedent soil moisture conditions.

A different aspect of the animal system included in a Monte Carlo simulation model described by Jorgensen (1997) is the spread of disease in slaughter pig units. Jorgensen (1997) suggests that Monte Carlo simulation models of animal production systems can be seen as representations of expert knowledge of the system. The model output, parameter, structure and equations used in the model all combine to make up the knowledge contained in the model (Jorgensen 1997).

B.6 Models Developed to Explore Sustainable Agriculture

The computer based environmental management system described by Lewis *et al.* (1997) was developed with a view to encourage more sustainable farming practices. The software is both a decision analysis and a decision support system. The core of this environmental management system is an assessment mode that measures environmental performance by deriving unique indices that are called eco-ratings (Lewis *et al.* 1997). Incorporated into this environmental management system is a module for soil sustainability that seeks to ensure that the soil, as a natural resource, is fully preserved. The key factors for soil sustainability identified by Lewis *et al.* (1997) are maintaining the levels of the major nutrients (N, P, K), trace elements and organic matter.

In the model described by Lewis *et al.* (1997) a sustainability threshold is defined as a neutral activity, that is, in their eco-rating scoring system, an activity that scores a zero. In this system the practices should be modified so that the eco-ratings achieved in the program are as high as possible. The eco-rating can take on values from –100 to 100. The environmental management system described by Lewis *et al.* (1997) is also described as a monitoring tool, comparable with the ISO14001 system.

Two other models developed with a view to defining the best management practices for sustainability are ManureN and WaterMod. ManureN has been described earlier and focuses on manure application and irrigation for the long term sustainability of the system (Sri Ranjan *et al.* 1995). WaterMod (Johnson 1998) allows the investigation and study of the effect that different management practices have on the soil water in agricultural systems. Inputs to the model are rainfall and irrigation and the model calculates runoff, transpiration, evaporation, infiltration and through drainage by solving Richard's equations. The WaterMod model is designed to explore, among other things, sustainable irrigation and cropping strategies to reduce runoff and through drainage.

B.7 The Processes Required in a Model of an Agro-ecosystem

B.7.1 Crop Growth

Crop Growth is a function of many factors and those that are included in the models surveyed in the literature are also many and varied. The NTRM (Nitrogen-Tillage-Residue Management), EPIC, CENTURY and Manure N models are examples of the difference approaches used to model crop growth. Starting with the most complex, plant growth in the NTRM module is a function of photosynthesis, respiration, leaf area, grain filling, transpiration and nitrogen uptake (Shaffer 1985). Root growth in this model is also complicated and includes root extension, branching, and death (Shaffer 1985). The crop growth module in ManureN is simpler and relates cumulative dry matter production and evapotranspiration at optimum fertility and includes a yield reduction function for nitrogen concentrations in the toxic levels

(Sri Ranjan *et al.* 1995). EPIC and the CENTURY models use the least complex approach and simulate plant growth as a function of air temperature and water availability (Natural Resource Ecology Laboratory 1998; Parsons *et al.* 1995).

Aspects of crop growth considered important to include in the EMU model are yield reduction due to salinity effects and the ability to simulate different cropping cycles. A simple algorithm that required minimal input variables was also considered important.

B.7.2 Soil-Water Processes

As with crop growth, representation of the soil-water processes span one-dimensional mass balance methods to the use of finite differences to solve partial differential equations. There are several models that divide the soil profile up into an arbitrary number of layers.

SUBSTOR divides the soil profile into a maximum of 15 compartments with soil and plant parameters being defined for each layer (Mahdian & Gallichand 1995) and uses a daily water balance to calculate infiltration from runoff, irrigation and precipitation. In SUBSTOR the difference in water potential between each soil layer is used to drive water flow up and down the profile (Mahdian & Gallichand 1995). Iskander (1981) indicates the validity of one-dimensional water flow models, quoting excellent agreement between experimental data and numerically solved flow equations for several experiments.

There is a choice of two approaches in the CropSyst (Stockle 1996a) model to simulate the soil water – the first one utilises a finite difference solution of Richard's equation and the second a cascading approach (Stockle 1996a). Richard's equation is also used in the WaterMod model (Johnson 1998).

The biggest limitation in modelling soil-water systems appears to be the difficulties associated with estimating the parameters that drive the soil-water system. There is limited affordable technology available for monitoring, analysing, and predicting soil-water regimes (Iskander 1981) and using theoretical and lower limits of water availability (wilting point) is not sufficiently precise to be much more than a rough index (Ritchie 1981). One of the biggest problems in defining limits of water availability to use in modelling the soil water balance is obtaining accurate estimates of soil water potential from soil samples (Ritchie 1981).

The SCS curve number method is used in many models to estimate runoff and appears to produce the best results for wet catchments due to relatively well-defined rainfall-runoff process operating in these conditions (Grayson & Chiew 1994; Mahdian & Gallichand 1995; Stockle 1996a). Another approach is to partition rainfall into different storages, with the excess becoming runoff. WaterMod uses this method effectively and routes any surface water in excess of the maximum surface storage to runoff (Johnson 1998).

B.7.3 Nutrients

Representing the many nitrogen transformations and processes has been the focus of many modelling exercises, with many models also including phosphorus modules. In contrast there are relatively few models that consider the cation balance. Some examples of the different approaches taken in modelling these aspects are outlined in the following sections.

B.7.3.1 Nitrogen and Phosphorus Models

ManureN computes ammonia volatilisation losses after manure application and accounts for the soil nitrogen by a mass balance, taking into account mineralisation of previously applied manure and crop uptake (Sri Ranjan *et al.* 1995). Biological transformation of the nitrogen in the manure is based on biological time scales and is assumed to proceed on an actual time scale when the soil temperature is 10°C, the soil moisture is at field capacity and pH is 7.0. The actual time is transformed to a biological time increment that would give the same conversion rate that would take place under the reference condition for different soil conditions (Sri Ranjan *et al.* 1995).

The EPIC model partitions organic nutrients into nitrogen and phosphorus pools (Parsons *et al.* 1995). Nutrients become available for plant uptake and leaching as a function of organic carbon, soil temperature and moisture, soil particle proportion, and other factors in the nitrogen and phosphorus cycles (these factors are not stated) (Parsons *et al.* 1995). Another approach is provided by the CREAMS nutrient submodel, which incorporates an active zone of 10mm at the top of the surface, where soluble nutrients are assumed to be available for extraction into runoff and leaching (Saleh *et al.* 1994).

Detailed nitrogen transformations are included in the CropSyst model; net mineralisation, nitrification, denitrification, ammonium sorption, symbiotic N fixation, crop N demand crop N uptake (Stockle 1996a). The distribution of nitrogen throughout the profile is linked with the water distribution module. Chemical budgets of pesticides and salinity are also kept and interact with the water balance (Stockle 1996a).

Two independent submodels, with the desired submodel being selected by the user, can simulate nitrogen transformations in the NTRM model (Shaffer 1985). In the first submodel, nitrification, denitrification, urea hydrolysis, mineralisation, and immobilisation are simulated using a combination of regression equations, and first and zero order rate process equations (Shaffer 1985). In this submodel there is a transition state equation for nitrification, which is a function of soil temperature, NH_4^+, O_2, and H^+ concentrations, apparent activation energy and the combined effects of soil water content and salinity. The second submodel simulates C and N transformations and includes nitrification, mineralisation, immobilisation, and nonsymbiotic N_2 fixation (Shaffer 1985). The nitrogen transformation rates are zero and first-order rate process equations that are a function of soil water content and temperature (Shaffer 1985).

The denitrification algorithm used in CREAMS is a function of drainage, and if drainage is occurring it is assumed the soil is above field capacity and anaerobic conditions persist and therefore denitrification occurs (Saleh *et al.* 1994). The CENTURY model has different potential decomposition rates for three pools of soil organic matter – active, slow and passive (Natural Resource Ecology Laboratory 1998).

B.7.3.2 Cation Models

The SAFE model uses the Gapon exchange equations to model the cations exchange complex. The Gapon exchange equations relate the concentrations of each of the cations in solution to those adsorbed onto the exchange sites and requires the use of an iterative method to solve for the concentrations of each cation as a function of the cation exchange capacity. A rate equation, which is a function of the concentration difference between the surface of the exchange complex and the concentration in the soil solution, is also used in conjunction with the Gapon exchange equations in the SAFE model, which requires the computation of pH at the exchange phase surface (Sverdrup *et al.* 1995).

The NTRM model includes a chemical equilibrium submodel that simulates several processes considered significant in alkaline or neutral soil-water systems (Shaffer 1985). The solute chemistry simulated includes dissolution-precipitation reactions for calcium carbonate and calcium sulfate, ion exchange of Ca^{2+}, Mg^{2+}, Na^{+}, and NH_4^{+}, dissociation reactions for carbonic acid, and ion pairing of Ca^{2+}, Mg^{2+}, and Na^{+} with SO_4^{2-}. This submodel was found to have the greatest application in irrigated semiarid to arid regions (Shaffer 1985). However Sverdrup *et al.* (1995) cautions against modelling the cation exchange as an equilibrium reaction, as episodic variations in flow intensity and soil solution composition due to inputs may mask short-term dynamics and cause incorrect long-term trends.

B.8 Conclusions

This appendix does not purport to be a comprehensive review of all the models that are currently available for research of the agro-ecosystem. Rather, it provides an overview of the types of models that have been developed recently and the trend to decision support systems that have practical application for the farmer. Of most significance is the move away from deterministic to stochastic models that incorporate the variability inherent in a system driven by hydrological variables.

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Appendix C. Monthly Rainfall Probability Distributions

January

i	Rainfall	Probability Density
0	0	0.088
1	5	0.038
2	10	0.032
3	15	0.010
4	20	0.007
5	25	0.007
6	30	0.001
7	35	0.001
8	40	0.003
9	45	0.001
10	50	0.001
11	55	0.000
12	60	0.000
13	65	0.001
14	70	0.000
15	75	0.001

February

i	Rainfall	Probability Density
0	0	0.101
1	5	0.043
2	10	0.015
3	15	0.014
4	20	0.010
5	25	0.005
6	30	0.000
7	35	0.007
8	40	0.000
9	45	0.003
10	50	0.000
11	55	0.000
12	60	0.000
13	65	0.000
14	70	0.000
15	75	0.000
16	80	0.000
17	85	0.000
18	90	0.000
19	95	0.002

March

i	Rainfall	Probability Density
0	0	0.092
1	5	0.047
2	10	0.019
3	15	0.011
4	20	0.008
5	25	0.008
6	30	0.006
7	35	0.003
8	40	0.003
9	45	0.000
10	50	0.003

April

i	Rainfall	Probability Density
0	0	0.119
1	5	0.024
2	10	0.022
3	15	0.010
4	20	0.008
5	25	0.008
6	30	0.010

May

i	Rainfall	Probability Density
0	0	0.113
1	5	0.034
2	10	0.012
3	15	0.014
4	20	0.004
5	25	0.012
6	30	0.002
7	35	0.004
8	40	0.002
9	45	0.000
10	50	0.000
11	55	0.000
12	60	0.000
13	65	0.000
14	70	0.002

June

i	Rainfall	Probability Density
0	0	0.143
1	5	0.025
2	10	0.012
3	15	0.006
4	20	0.004
5	25	0.008
6	30	0.000
7	35	0.000
8	40	0.000
9	45	0.002

July

i	Rainfall	Probability Density
0	0	0.123
1	5	0.030
2	10	0.020
3	15	0.006
4	20	0.008
5	25	0.005
6	30	0.002
7	35	0.006
8	40	0.000
9	45	0.000
10	50	0.002

August

i	Rainfall	Probability Density
0	0	0.125
1	5	0.038
2	10	0.017
3	15	0.010
4	20	0.010

September

i	Rainfall	Probability Density
0	0	0.126
1	5	0.034
2	10	0.017
3	15	0.008
4	20	0.009
5	25	0.004
6	30	0.002

October

i	Rainfall	Probability Density
0	0	0.112
1	5	0.040
2	10	0.023
3	15	0.008
4	20	0.005
5	25	0.003
6	30	0.003
7	35	0.005

November

i	Rainfall	Probability Density
0	0	0.089
1	5	0.058
2	10	0.015
3	15	0.024
4	20	0.006
5	25	0.004
6	30	0.001
7	35	0.001
8	40	0.000
9	45	0.000
10	50	0.001

December

i	Rainfall	Probability Density
0	0	0.093
1	5	0.036
2	10	0.024
3	15	0.016
4	20	0.008
5	25	0.008
6	30	0.003
7	35	0.005
8	40	0.001
9	45	0.003
10	50	0.000
11	55	0.000
12	60	0.001

Appendix D. Monthly Evaporation Probability Distributions

January

i	Evaporation	Probability Density
0	0	0.079
1	0.5	0.026
2	1	0.026
3	1.5	0.026
4	2	0.026
5	2.5	0.053
6	3	0.211
7	3.5	0.132
8	4	0.079
9	4.5	0.132
10	5	0.132
11	5.5	0.342
12	6	0.211
13	6.5	0.237
14	7	0.158
15	7.5	0.132

February

i	Evaporation	Probability Density
0	0	0.057
1	0.5	0.086
2	1	0.057
3	1.5	0.086
4	2	0.057
5	2.5	0.000
6	3	0.143
7	3.5	0.171
8	4	0.057
9	4.5	0.171
10	5	0.286
11	5.5	0.114
12	6	0.429
13	6.5	0.114
14	7	0.171

March

i	Evaporation	Probability Density
0	0	0.000
1	0.5	0.000
2	1	0.032
3	1.5	0.000
4	2	0.000
5	2.5	0.065
6	3	0.161
7	3.5	0.258
8	4	0.194
9	4.5	0.581
10	5	0.419
11	5.5	0.258
12	6	0.032

April

i	Evaporation	Probability Density
0	0	0.1
1	0.5	0.133
2	1	0.100
3	1.5	0.100
4	2	0.200
5	2.5	0.267
6	3	0.300
7	3.5	0.333
8	4	0.300
9	4.5	0.133
10	5	0.033
11	5.5	

May

i	Evaporation	Probability Density
0	0	0.258
1	0.5	0.226
2	1	0.452
3	1.5	0.548
4	2	0.258
5	2.5	0.194
6	3	0.032
7	3.5	0.032

June

i	Evaporation	Probability Density
0	0	0.346
1	0.5	0.370
2	1	0.617
3	1.5	0.519
4	2	0.148

July

i	Evaporation	Probability Density
0	0	0.32
1	0.5	0.32
2	1	0.58
3	1.5	0.44
4	2	0.3
5	2.5	0.04

August

i	Evaporation	Probability Density
0	0	0.065
1	0.5	0.114
2	1	0.146
3	1.5	0.407
4	2	0.341
5	2.5	0.520
6	3	0.341
7	3.5	0.065

September

i	Evaporation	Probability Density
0	0	0.152
1	0.5	0.025
2	1	0.076
3	1.5	0.203
4	2	0.177
5	2.5	0.278
6	3	0.430
7	3.5	0.329
8	4	0.203
9	4.5	0.101
10	5	0.025

October

i	Evaporation	Probability Density
0	0	0.044
1	0.5	0.044
2	1	0.178
3	1.5	0.000
4	2	0.089
5	2.5	0.089
6	3	0.178
7	3.5	0.267
8	4	0.044
9	4.5	0.089
10	5	0.311
11	5.5	0.489
12	6	0.089
13	6.5	0.044
14	7	0.044

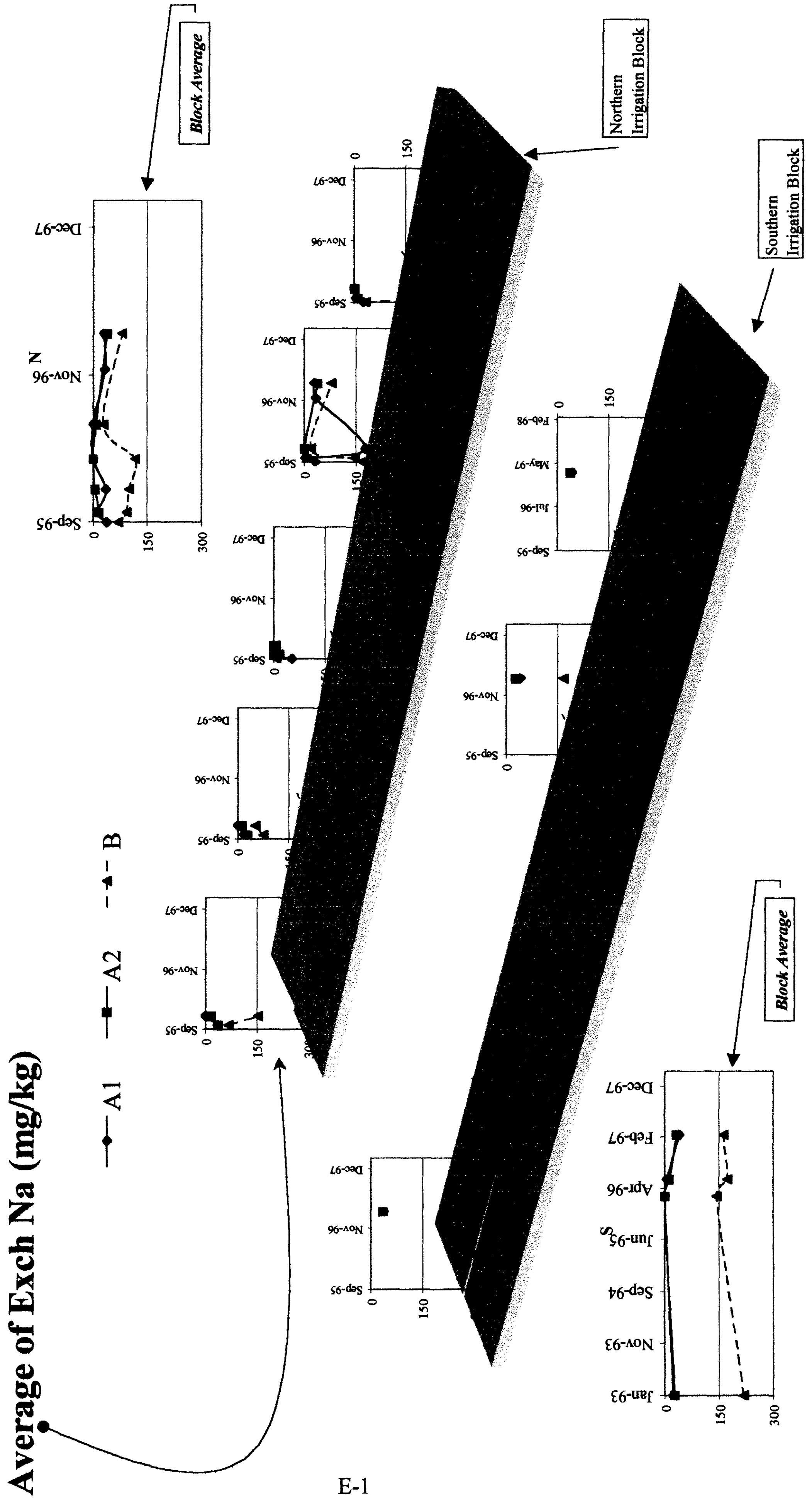
November

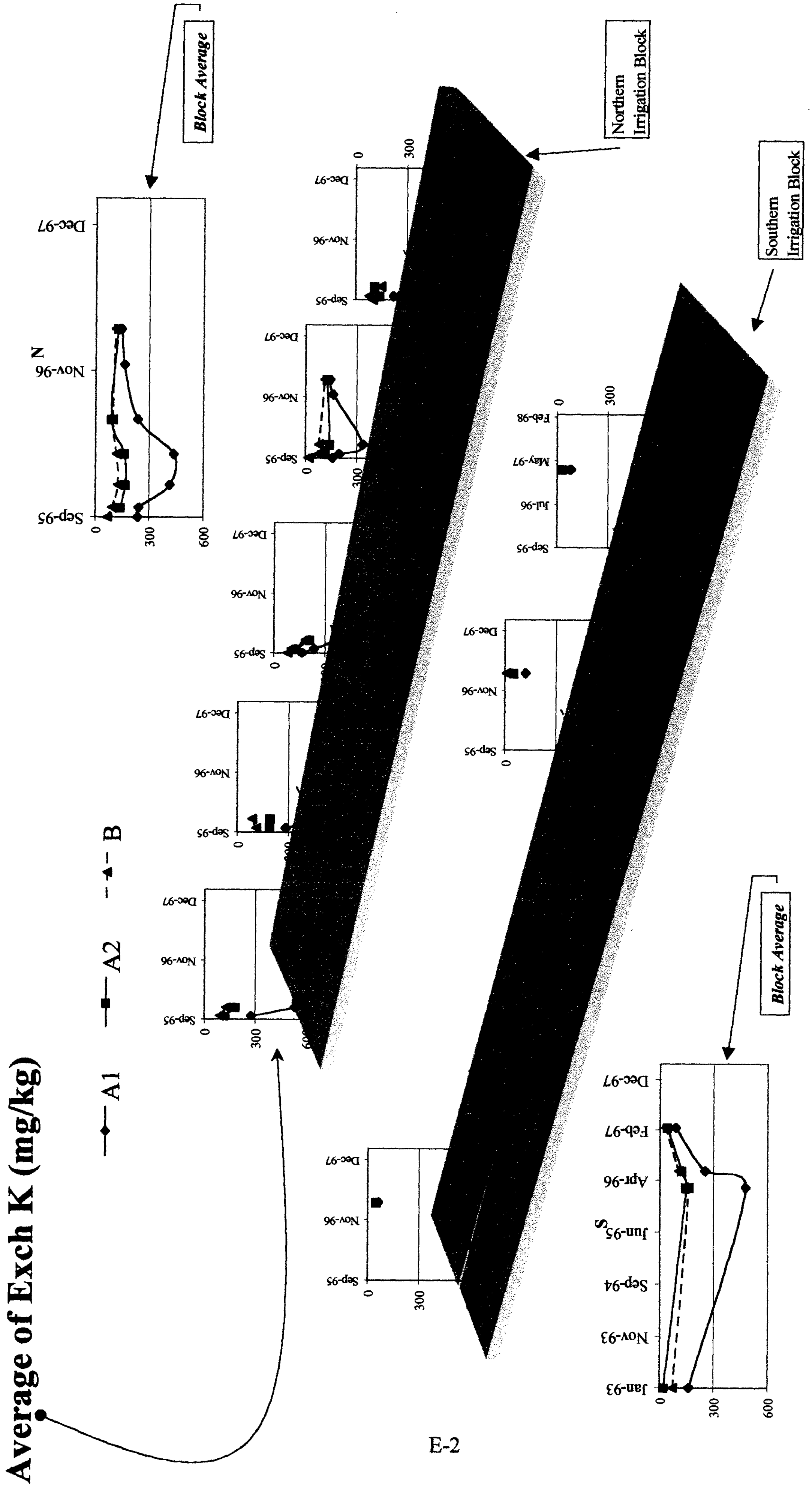
i	Evaporation	Probability Density
0	0	0.000
1	0.5	0.000
2	1	0.149
3	1.5	0.060
4	2	0.030
5	2.5	0.060
6	3	0.119
7	3.5	0.179
8	4	0.030
9	4.5	0.119
10	5	0.119
11	5.5	0.299
12	6	0.269
13	6.5	0.209
14	7	0.119
15	7.5	0.149
16	8	0.090

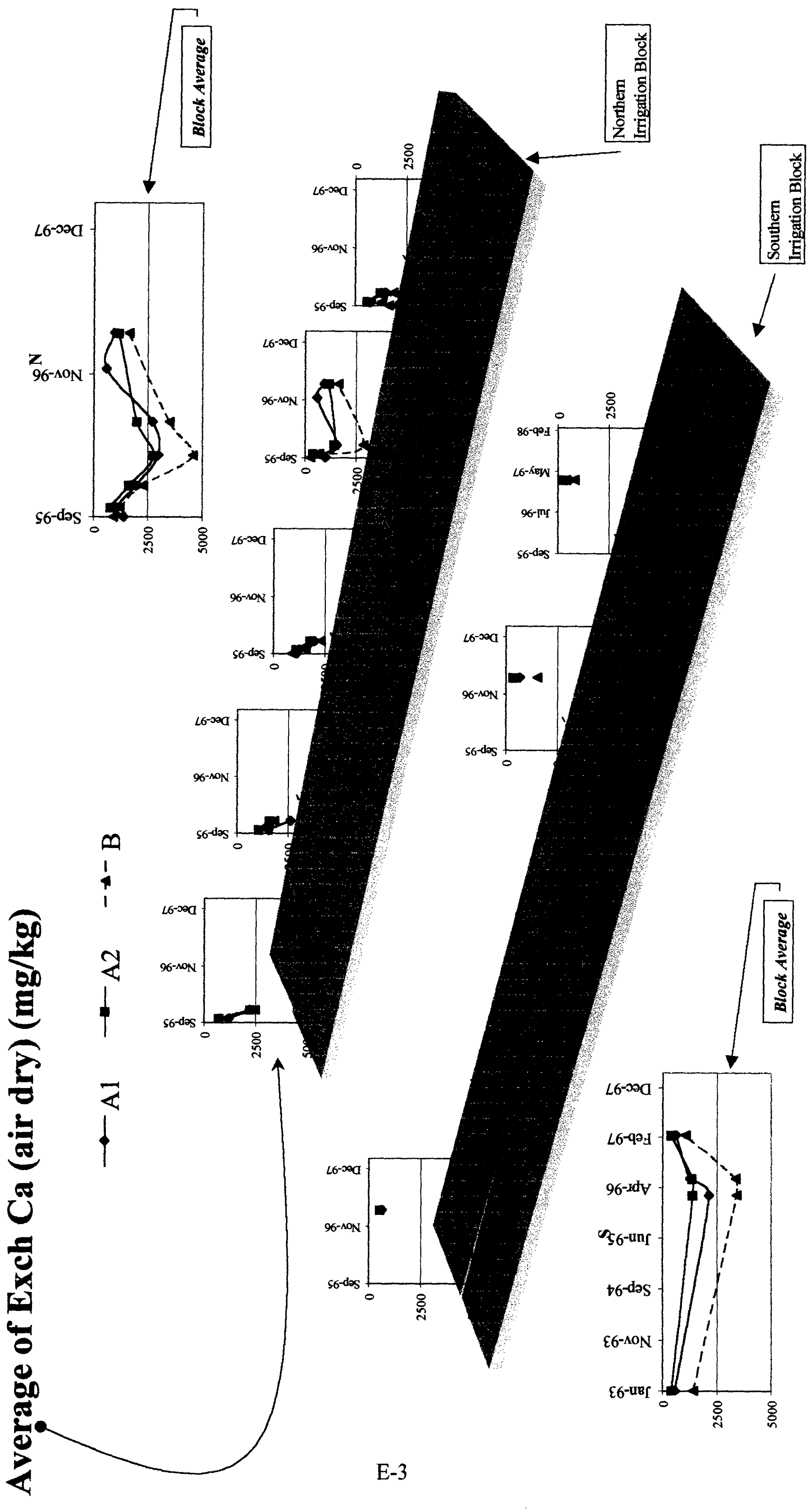
December

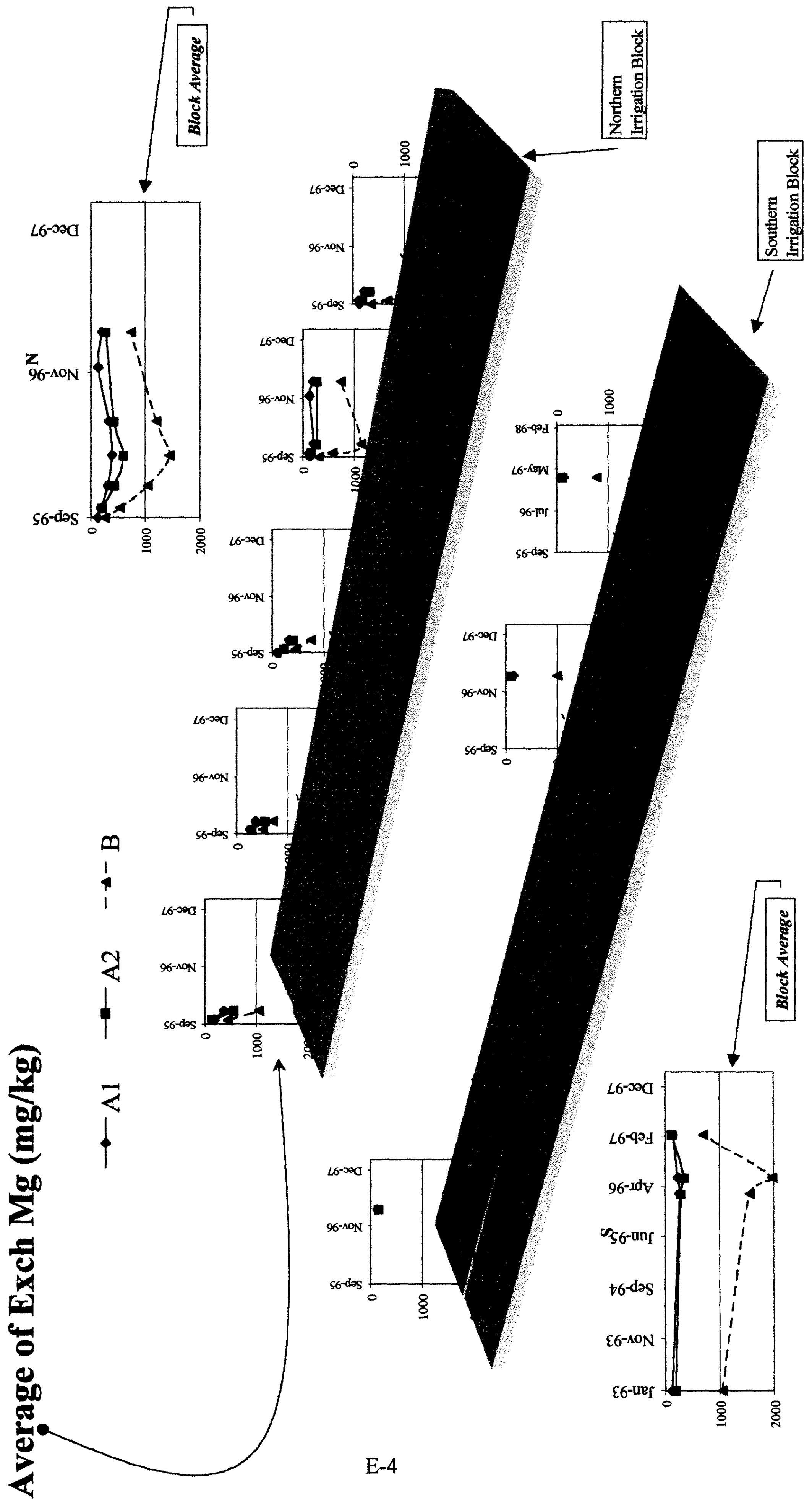
i	Evaporation	Probability Density
0	0	0.029
1	0.5	0.029
2	1	0.029
3	1.5	0.029
4	2	0.088
5	2.5	0.147
6	3	0.000
7	3.5	0.059
8	4	0.088
9	4.5	0.059
10	5	0.176
11	5.5	0.147
12	6	0.235
13	6.5	0.265
14	7	0.235
15	7.5	0.294
16	8	0.088

Appendix E: Soil Measurements Over Last 3 Years

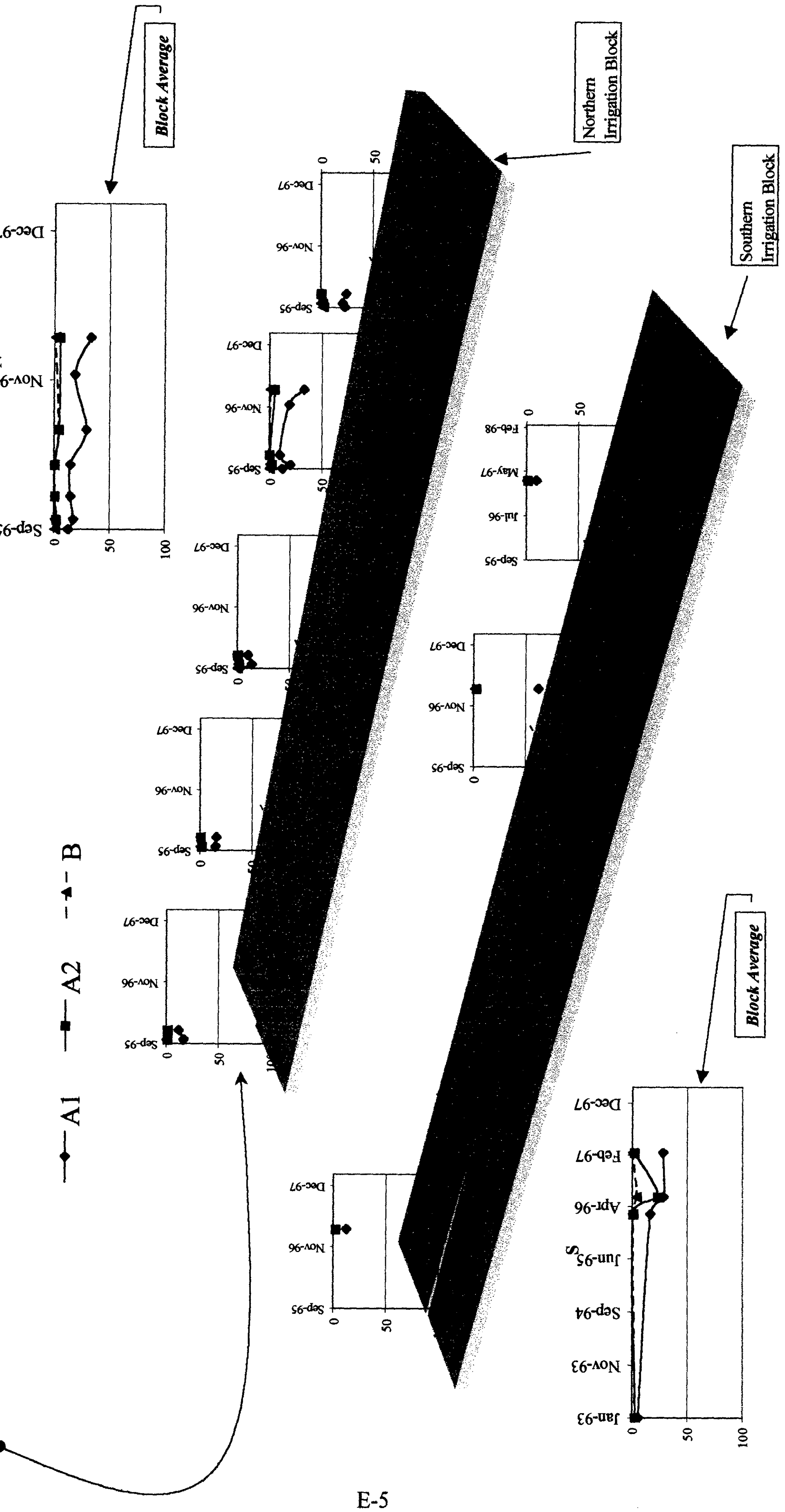



Average of Exch K (mg/kg)
A1
A2
B
Block Average
N
Northern Irrigation Block
Southern Irrigation Block
S
Block Average
Sep-95
Nov-96
Dec-97
Jul-96
May-97
Feb-98
Jan-93
Nov-93
Sep-94
Jun-95
Apr-96
Feb-97
0
300
600

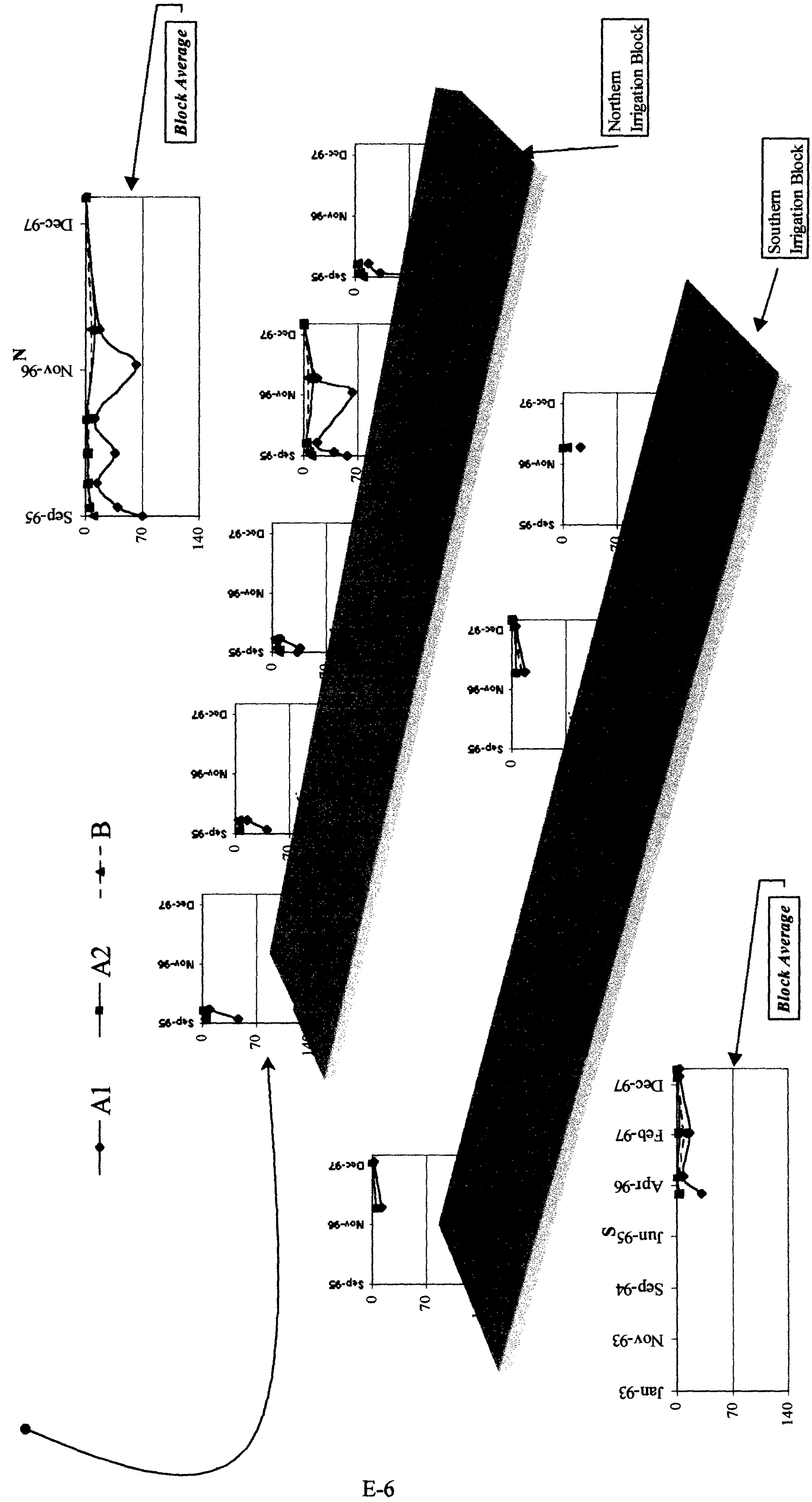

Average of Exch Ca (air dry) (mg/kg)
A1
A2
B
Block Average
Northern Irrigation Block
Southern Irrigation Block
Block Average
N
S
Sep-95
Nov-96
Dec-97
Jul-96
May-97
Feb-98
Jan-93
Nov-93
Sep-94
Jun-95
Apr-96
Feb-97
0
2500
5000

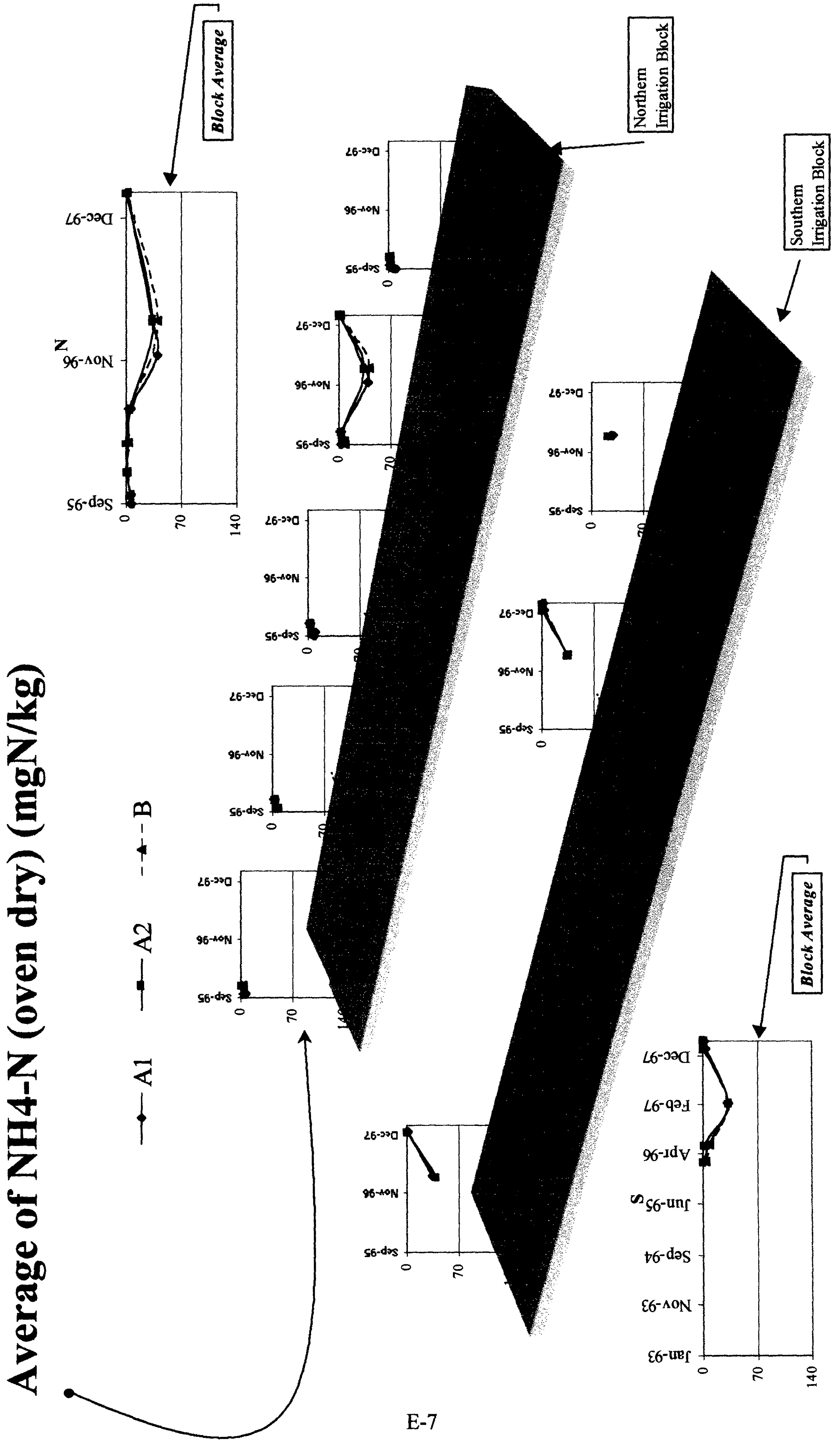

Average of Exch Mg (mg/kg)
A1
A2
B
Block Average
Northern Irrigation Block
Southern Irrigation Block
Block Average
N
S
Sep-95
Nov-96
Dec-97
Jan-93
Nov-93
Sep-94
Jun-95
Apr-96
Feb-97
Jul-96
May-97
Feb-98
0
1000
2000

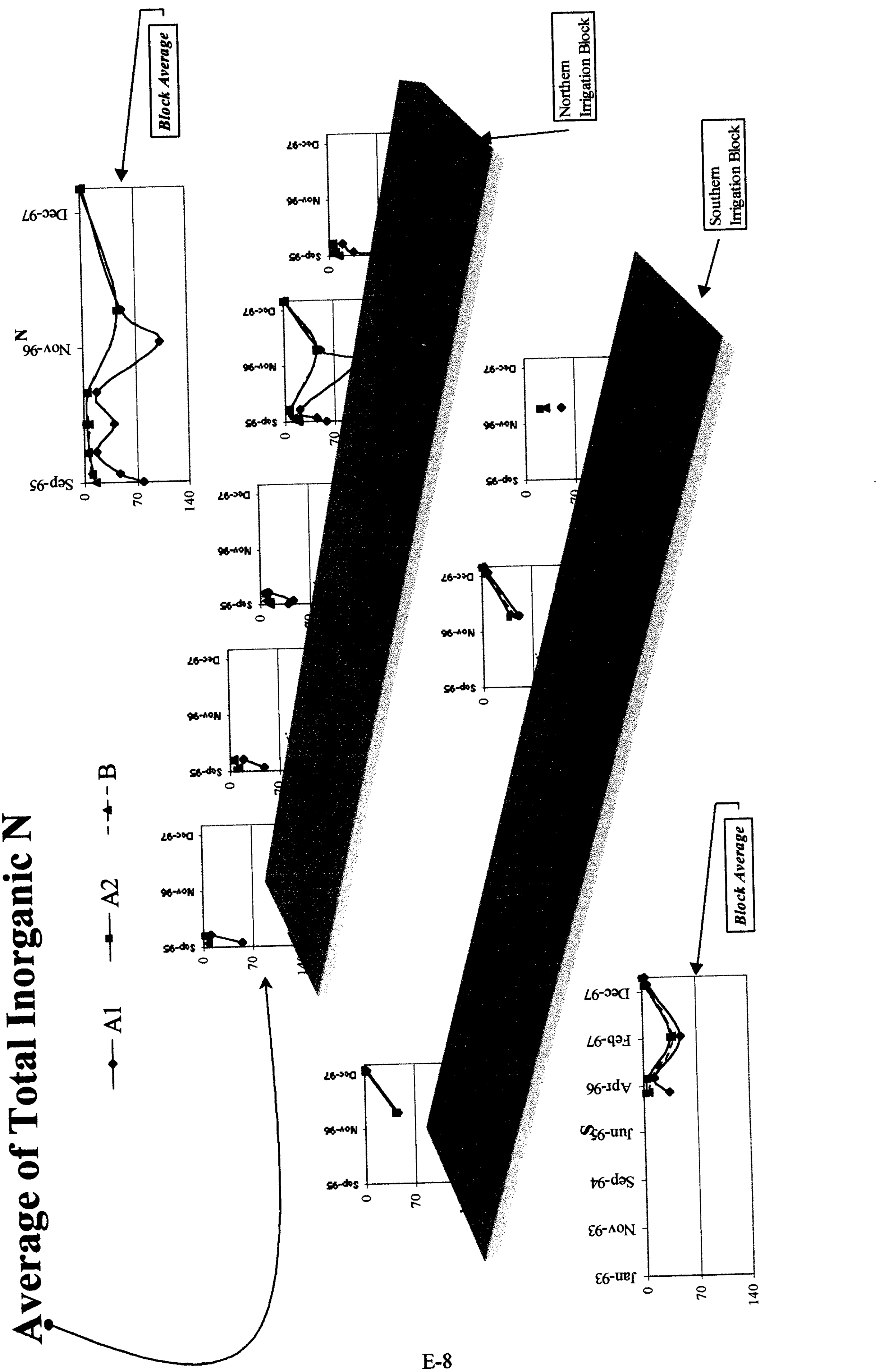
Average of P BrayI (mg/kg)



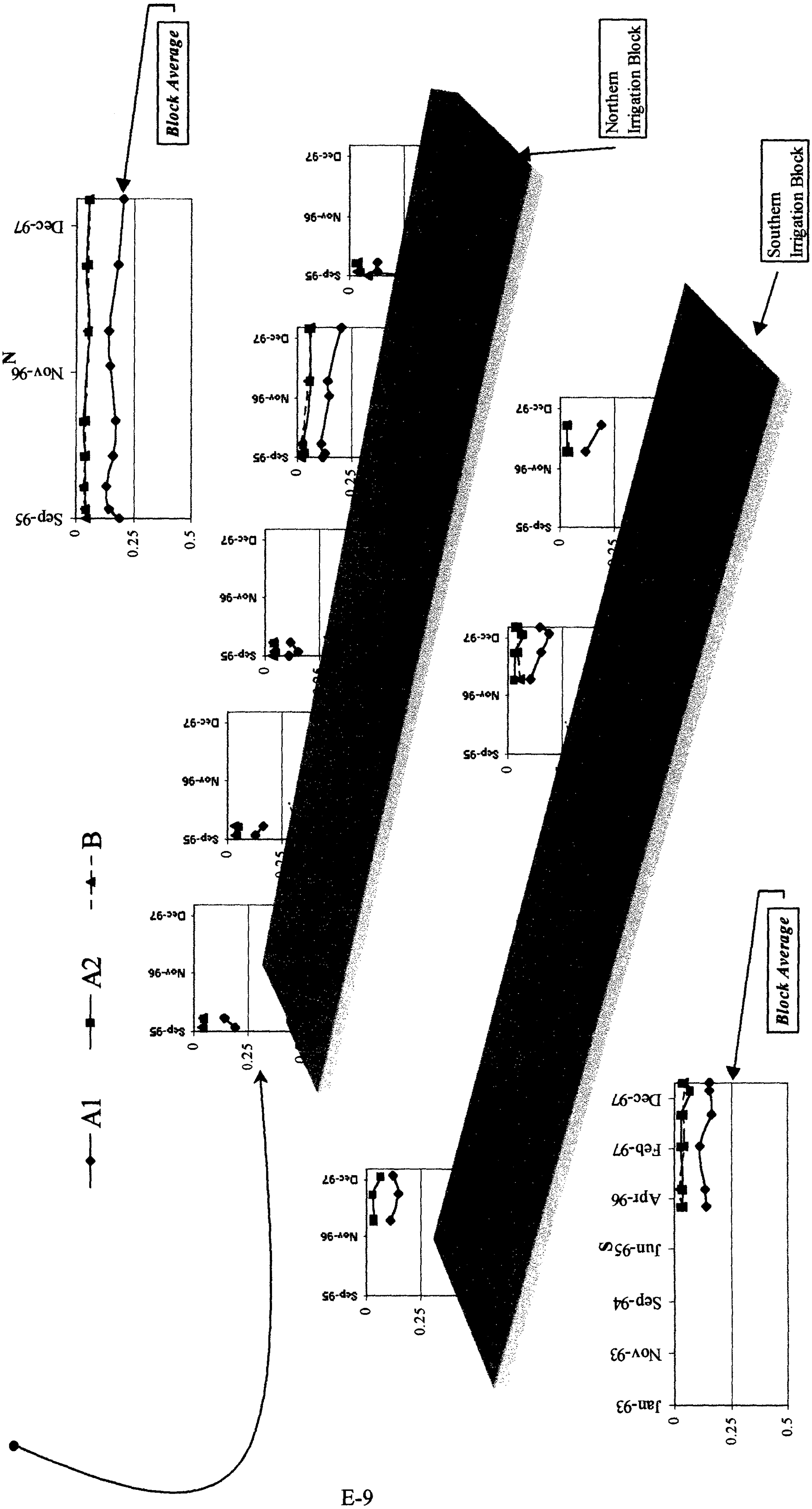
Average of NO3-N (oven dry) (mgN/kg)




Average of NH4-N (oven dry) (mgN/kg)
A1
A2
B
Block Average
Northern Irrigation Block
Southern Irrigation Block
Block Average
N
S
0
70
140
Sep-95
Nov-96
Dec-97
Jan-93
Nov-93
Sep-94
Jun-95
Apr-96
Feb-97


Average of Total Inorganic N
A1
A2
B
Block Average
N
Northern Irrigation Block
Southern Irrigation Block
Block Average
S
0
70
140
Sep-95
Nov-96
Dec-97
Jan-93
Nov-93
Sep-94
Jun-95
Apr-96
Feb-97
Dec-97

Average of TKN (oven dry) (%)



Appendix F. Analysis of Variance for Crop Uptake as a Function of "mu"

```
Results of Hypothesis Test
--------------------------

Alternative Hypothesis:         two.sided

Test Name:                  Kruskal-Wallis rank sum test

Data:                       na and mu from data frame compare.model.output

Test Statistic:                     Kruskal-Wallis chi-square = 13.59712

Test Statistic Parameter:   df = 4

P-value:                    0.00869835
```

```
Results of Hypothesis Test
--------------------------

Alternative Hypothesis:         two.sided

Test Name:                  Kruskal-Wallis rank sum test

Data:                       k and mu from data frame compare.model.output

Test Statistic:                     Kruskal-Wallis chi-square = 13.5

Test Statistic Parameter:   df = 4

P-value:                    0.009074317
```

```
Results of Hypothesis Test
--------------------------

Alternative Hypothesis:         two.sided

Test Name:                  Kruskal-Wallis rank sum test

Data:                       ca and mu from data frame compare.model.output

Test Statistic:                     Kruskal-Wallis chi-square = 13.00478

Test Statistic Parameter:   df = 4

P-value:                    0.01125247
```

```
Results of Hypothesis Test
--------------------------

Alternative Hypothesis:         two.sided

Test Name:                  Kruskal-Wallis rank sum test

Data:                       mg and mu from data frame compare.model.output

Test Statistic:                     Kruskal-Wallis chi-square = 13.00478

Test Statistic Parameter:   df = 4

P-value:                    0.01125247
```

```
Results of Hypothesis Test
--------------------------

Alternative Hypothesis:          two.sided

Test Name:                   Kruskal-Wallis rank sum test

Data:                        p and mu from data frame compare.model.output

Test Statistic:                  Kruskal-Wallis chi-square = 12.9

Test Statistic Parameter:    df = 4

P-value:                     0.01177489
```

```
***  One-Way ANOVA for data in n by mu ***

Call:
   aov(formula = structure(.Data = n ~ mu, class = "formula"),
       data = compare.model.output)

Terms:
                       mu Residuals
 Sum of Squares 3940.706  3114.733
Deg. of Freedom        4        10

Residual standard error: 17.64861
Estimated effects are balanced

          Df Sum of Sq  Mean Sq  F Value      Pr(F)
       mu  4  3940.706 985.1765 3.162956 0.06359593
Residuals 10  3114.733 311.4733
```

Appendix G. Analysis of Variance for Crop Uptake as a Function of "w90"

```
Alternative Hypothesis:             two.sided

Test Name:                     Kruskal-Wallis rank sum test

Data:                          na and w90 from data frame compare.model.output

Test Statistic:                     Kruskal-Wallis chi-square = 13.62162

Test Statistic Parameter:      df = 4

P-value:                       0.008605945
```

```
Results of Hypothesis Test
--------------------------

Alternative Hypothesis:             two.sided

Test Name:                     Kruskal-Wallis rank sum test

Data:                          k and w90 from data frame compare.model.output

Test Statistic:                     Kruskal-Wallis chi-square = 13.62162

Test Statistic Parameter:      df = 4

P-value:                       0.008605945

Results of Hypothesis Test
--------------------------

Alternative Hypothesis:             two.sided

Test Name:                     Kruskal-Wallis rank sum test

Data:                          ca and w90 from data frame compare.model.output

Test Statistic:                     Kruskal-Wallis chi-square = 13.62162

Test Statistic Parameter:      df = 4

P-value:                       0.008605945
```

```
Results of Hypothesis Test
--------------------------

Alternative Hypothesis:             two.sided

Test Name:                     Kruskal-Wallis rank sum test

Data:                          mg and w90 from data frame compare.model.output

Test Statistic:                     Kruskal-Wallis chi-square = 13.62162

Test Statistic Parameter:      df = 4

P-value:                       0.008605945
```

```
Results of Hypothesis Test
--------------------------

Alternative Hypothesis:             two.sided

Test Name:                   Kruskal-Wallis rank sum test

Data:                        n and w90 from data frame compare.model.output

Test Statistic:                     Kruskal-Wallis chi-square = 11.83333

Test Statistic Parameter:    df = 4

P-value:                     0.01863465
```

```
Results of Hypothesis Test
--------------------------

Alternative Hypothesis:             two.sided

Test Name:                   Kruskal-Wallis rank sum test

Data:                        p and w90 from data frame compare.model.output

Test Statistic:                     Kruskal-Wallis chi-square = 13.62162

Test Statistic Parameter:    df = 4

P-value:                     0.008605945
```

Appendix H. Analysis of Variance for Nitrogen Crop Deficiency as a Function of "w90" and "mu"

```
Results of Hypothesis Test
--------------------------

Alternative Hypothesis:          two.sided

Test Name:                  Kruskal-Wallis rank sum test

Data:                       n and mu from data frame compare.model.output

Test Statistic:                  Kruskal-Wallis chi-square = 8.4

Test Statistic Parameter:   df = 4

P-value:                    0.077977
```

```
Results of Hypothesis Test
--------------------------

Alternative Hypothesis:          two.sided

Test Name:                  Kruskal-Wallis rank sum test

Data:                       n and w90 from data frame compare.model.output

Test Statistic:                  Kruskal-Wallis chi-square = 12.23333

Test Statistic Parameter:   df = 4

P-value:                    0.01569792
```

Appendix I. Analysis of Variance for Drainage Output as a Function of "mu"

```
***  One-Way ANOVA for data in na by mu ***

Call:
   aov(formula = structure(.Data = na ~ mu, class = "formula"),
       data = compare.model.output)

Terms:
                      mu Residuals
 Sum of Squares 2127.881  5903.595
Deg. of Freedom        4        10

Residual standard error: 24.29731
Estimated effects are balanced

          Df Sum of Sq  Mean Sq   F Value     Pr(F)
       mu  4  2127.881 531.9702 0.9010954 0.4988562
Residuals 10  5903.595 590.3595
```

```
***  One-Way ANOVA for data in k by mu ***

Call:
   aov(formula = structure(.Data = k ~ mu, class = "formula"),
       data = compare.model.output)

Terms:
                      mu Residuals
 Sum of Squares 34.16901  17.75466
Deg. of Freedom        4        10

Residual standard error: 1.332466
Estimated effects are balanced

          Df Sum of Sq  Mean Sq  F Value      Pr(F)
       mu  4  34.16901 8.542252 4.811273 0.02005506
Residuals 10  17.75466 1.775466
```

```
       ***  One-Way ANOVA for data in ca by mu ***

Call:
   aov(formula = structure(.Data = ca ~ mu, class = "formula"),
       data = compare.model.output)

Terms:
                      mu Residuals
 Sum of Squares  42.7147  789.2575
Deg. of Freedom        4        10

Residual standard error: 8.884017
Estimated effects are balanced

          Df Sum of Sq  Mean Sq   F Value     Pr(F)
       mu  4   42.7147 10.67867 0.1353002 0.9655699
Residuals 10  789.2575 78.92575
```

Appendix I: Analysis of Variance for Drainage Output as a Function of "mu"

```
***  One-Way ANOVA for data in mg by mu ***

Call:
   aov(formula = structure(.Data = mg ~ mu, class = "formula"),
       data = compare.model.output)

Terms:
                      mu Residuals
 Sum of Squares   48.718  1181.371
Deg. of Freedom        4        10

Residual standard error: 10.86909
Estimated effects are balanced

          Df Sum of Sq  Mean Sq   F Value      Pr(F)
       mu  4    48.718  12.1796 0.1030973 0.9788475
Residuals 10  1181.371 118.1371
```

```
***  One-Way ANOVA for data in inorgn by mu ***

Call:
   aov(formula = structure(.Data = inorgn ~ mu, class = "formula"
       ), data = compare.model.output)

Terms:
                      mu Residuals
 Sum of Squares 1314.094   454.832
Deg. of Freedom        4        10

Residual standard error: 6.744125
Estimated effects are balanced

          Df Sum of Sq  Mean Sq  F Value       Pr(F)
       mu  4  1314.094 328.5235 7.222959 0.005298253
Residuals 10   454.832  45.4832
```

Appendix J. Analysis of Variance for Drainage Output as a Function of "w90"

```
Results of Hypothesis Test
--------------------------

Alternative Hypothesis:        two.sided

Test Name:                 Kruskal-Wallis rank sum test

Data:                      na and w90 from data frame compare.model.output

Test Statistic:                Kruskal-Wallis chi-square = 8.4

Test Statistic Parameter:  df = 4

P-value:                   0.077977
```

```
Results of Hypothesis Test
--------------------------

Alternative Hypothesis:        two.sided

Test Name:                 Kruskal-Wallis rank sum test

Data:                      k and w90 from data frame compare.model.output

Test Statistic:                Kruskal-Wallis chi-square = 4.424691

Test Statistic Parameter:  df = 4

P-value:                   0.3515708
```

```
***  One-Way ANOVA for data in ca by w90 ***

Call:
   aov(formula = structure(.Data = ca ~ w90, class = "formula"),
       data = compare.model.output)

Terms:
                     w90 Residuals
 Sum of Squares  571.291  1428.899
Deg. of Freedom        4        10

Residual standard error: 11.95366
Estimated effects are balanced

          Df Sum of Sq  Mean Sq   F Value     Pr(F)
      w90  4   571.291 142.8228 0.9995305 0.4517689
Residuals 10  1428.899 142.8899
```

```
***  One-Way ANOVA for data in mg by w90 ***

Call:
   aov(formula = structure(.Data = mg ~ w90, class = "formula"),
       data = compare.model.output)

Terms:
                      w90 Residuals
 Sum of Squares 1021.568  2022.185
Deg. of Freedom        4        10

Residual standard error: 14.22036
Estimated effects are balanced

          Df Sum of Sq  Mean Sq F Value     Pr(F)
      w90  4  1021.568 255.3920 1.26295 0.3466495
Residuals 10  2022.185 202.2185
```

```
***  One-Way ANOVA for data in inorgn by w90 ***

Call:
   aov(formula = structure(.Data = inorgn ~ w90, class =
       "formula"), data = compare.model.output)

Terms:
                      w90 Residuals
 Sum of Squares 924.8987  204.7554
Deg. of Freedom        4        10

Residual standard error: 4.524991
Estimated effects are balanced

          Df Sum of Sq  Mean Sq  F Value        Pr(F)
      w90  4  924.8987 231.2247 11.29273 0.0009965176
Residuals 10  204.7554  20.4755
```

Appendix K. Analysis of Variance for Runoff Output as a Function of "mu"

```
***  One-Way ANOVA for data in na by mu ***

Call:
   aov(formula = structure(.Data = na ~ mu, class = "formula"),
       data = compare.model.output)

Terms:
                      mu Residuals
 Sum of Squares 14140.15  19455.72
Deg. of Freedom        4        10

Residual standard error: 44.10864
Estimated effects are balanced

          Df Sum of Sq  Mean Sq  F Value     Pr(F)
       mu  4  14140.15 3535.038 1.816965 0.2022048
Residuals 10  19455.72 1945.572
```

```
***  One-Way ANOVA for data in k by mu ***

Call:
   aov(formula = structure(.Data = k ~ mu, class = "formula"),
       data = compare.model.output)

Terms:
                      mu Residuals
 Sum of Squares 22176.09  17218.82
Deg. of Freedom        4        10

Residual standard error: 41.49557
Estimated effects are balanced

          Df Sum of Sq  Mean Sq  F Value      Pr(F)
       mu  4  22176.09 5544.023 3.219745 0.06085051
Residuals 10  17218.82 1721.882
```

```
***  One-Way ANOVA for data in ca by mu ***

Call:
   aov(formula = structure(.Data = ca ~ mu, class = "formula"),
       data = compare.model.output)

Terms:
                      mu Residuals
 Sum of Squares 9183.521  7400.115
Deg. of Freedom        4        10

Residual standard error: 27.20315
Estimated effects are balanced

          Df Sum of Sq  Mean Sq  F Value      Pr(F)
       mu  4  9183.521 2295.880 3.102493 0.06668106
Residuals 10  7400.115  740.012
```

```
***  One-Way ANOVA for data in mg by mu ***

Call:
   aov(formula = structure(.Data = mg ~ mu, class = "formula"),
       data = compare.model.output)

Terms:
                      mu Residuals
 Sum of Squares  758.400  1244.146
Deg. of Freedom        4        10

Residual standard error: 11.15413
Estimated effects are balanced

          Df Sum of Sq  Mean Sq  F Value     Pr(F)
       mu  4   758.400 189.6000 1.523937 0.2678436
Residuals 10  1244.146 124.4146
```

```
***  One-Way ANOVA for data in orthop by mu ***

Call:
   aov(formula = structure(.Data = orthop ~ mu, class = "formula"
       ), data = compare.model.output)

Terms:
                      mu Residuals
 Sum of Squares 2665.445  6097.268
Deg. of Freedom        4        10

Residual standard error: 24.69265
Estimated effects are balanced

          Df Sum of Sq  Mean Sq  F Value     Pr(F)
       mu  4  2665.445 666.3612 1.092885 0.4111871
Residuals 10  6097.268 609.7268
```

```
***  One-Way ANOVA for data in orgp by mu ***

Call:
   aov(formula = structure(.Data = orgp ~ mu, class = "formula"),
       data = compare.model.output)

Terms:
                      mu Residuals
 Sum of Squares  54.4164  119.2345
Deg. of Freedom        4        10

Residual standard error: 3.453034
Estimated effects are balanced

          Df Sum of Sq  Mean Sq  F Value     Pr(F)
       mu  4   54.4164 13.60411 1.140954 0.3917616
Residuals 10  119.2345 11.92345
```

```
     ***  One-Way ANOVA for data in lorgn by mu ***

Call:
   aov(formula = structure(.Data = lorgn ~ mu, class = "formula"),
       data = compare.model.output)

Terms:
                       mu Residuals
 Sum of Squares 4.735984  4.326251
Deg. of Freedom        4        10

Residual standard error: 0.6577424
Estimated effects are balanced

         Df Sum of Sq  Mean Sq  F Value      Pr(F)
       mu  4  4.735984 1.183996 2.736772 0.08958881
Residuals 10  4.326251 0.432625
```

```
Results of Hypothesis Test
--------------------------

Alternative Hypothesis:          two.sided

Test Name:                  Kruskal-Wallis rank sum test

Data:                       inorgn and mu from data frame compare.model.output

Test Statistic:                  Kruskal-Wallis chi-square = 8.7

Test Statistic Parameter:   df = 4

P-value:                    0.06905145
```

Appendix L. Cropping Cycle, Manure and Fertiliser Additions for 15 year Simulation

Table L.1 Cropping Cycle for "Tullimba" 15 Year Simulation

Crop	Planting Date	Harvest Date
oats	21-Mar-01	01-Nov-01
Sorghum	22-Jan-02	18-Mar-02
oats	05-May-02	01-Oct-02
Sorghum	27-Nov-02	24-Mar-03
oats	21-Mar-03	01-Nov-03
Sorghum	22-Jan-04	18-Mar-04
oats	05-May-04	01-Oct-04
Sorghum	27-Nov-04	24-Mar-05
oats	21-Mar-05	01-Nov-05
Sorghum	22-Jan-06	18-Mar-06
oats	05-May-06	01-Oct-06
Sorghum	27-Nov-06	24-Mar-07
oats	21-Mar-07	01-Nov-07
Sorghum	22-Jan-08	18-Mar-08
oats	05-May-08	01-Oct-08
Sorghum	27-Nov-08	24-Mar-09
oats	21-Mar-09	01-Nov-09
Sorghum	22-Jan-10	18-Mar-10
oats	05-May-10	01-Oct-10
Sorghum	27-Nov-10	24-Mar-11
oats	21-Mar-11	01-Nov-11
Sorghum	22-Jan-12	18-Mar-12
oats	05-May-12	01-Oct-12
Sorghum	27-Nov-12	24-Mar-13
oats	21-Mar-13	01-Nov-13
Sorghum	22-Jan-14	18-Mar-14
oats	05-May-14	01-Oct-14
Sorghum	27-Nov-14	24-Mar-15
oats	21-Mar-15	01-Nov-15

Table L.2 Manure Application for "Tullimba" 15 Year Simulation

Date	Manure Application (t/ha)
20-Nov-01	15
24-Nov-02	6.5
20-Nov-03	15
24-Nov-04	6.5
20-Nov-05	15
24-Nov-06	6.5
20-Nov-07	15
24-Nov-08	6.5
20-Nov-09	15
24-Nov-10	6.5
20-Nov-11	15
24-Nov-12	6.5
20-Nov-13	15
24-Nov-14	6.5
20-Nov-15	15

Table L.3. Fertiliser Additions for "Tullimba" 15 Year Simulation

Appendix M. ate	**Fertiliser**	**(kg/ha)**
27-Aug-01	Nitram	112
07-Jan-02	Super Phosphate	250
05-May-02	Super Phosphate	60
06-May-02	Urea	60
27-Nov-02	Starter 15	127
29-Jan-03	Urea	250
27-Aug-03	Nitram	112
07-Jan-04	Super Phosphate	250
05-May-04	Super Phosphate	60
06-May-04	Urea	60
27-Nov-04	Starter 15	127
29-Jan-05	Urea	250
27-Aug-05	Nitram	112
07-Jan-06	Super Phosphate	250
05-May-06	Super Phosphate	60
06-May-06	Urea	60
27-Nov-06	Starter 15	127
29-Jan-07	Urea	250
27-Aug-07	Nitram	112
07-Jan-08	Super Phosphate	250
05-May-08	Super Phosphate	60
06-May-08	Urea	60
27-Nov-08	Starter 15	127

29-Jan-09	Urea	250
27-Aug-09	Nitram	112
07-Jan-10	Super Phosphate	250
05-May-10	Super Phosphate	60
06-May-10	Urea	60
27-Nov-10	Starter 15	127
29-Jan-11	Urea	250
27-Aug-11	Nitram	112
07-Jan-12	Super Phosphate	250
05-May-12	Super Phosphate	60
06-May-12	Urea	60
27-Nov-12	Starter 15	127
29-Jan-13	Urea	250
27-Aug-13	Nitram	112
07-Jan-14	Super Phosphate	250
05-May-14	Super Phosphate	60
06-May-14	Urea	60
27-Nov-14	Starter 15	127
29-Jan-15	Urea	250
27-Aug-15	Nitram	112

Appendix M. Average Monthly Runoff and Drainage Depths

rate	month	Treatment	month_no	Runoff (mm/ha/month)	Drainage (mm/ha/month)
0	0	0 - 0	1	125.46	172.82
0	0	0 - 0	2	32.27	83.27
0	0	0 - 0	3	56.68	88.22
0	0	0 - 0	4	15.36	42.73
0	0	0 - 0	5	46.98	80.89
0	0	0 - 0	6	9.12	18.71
0	0	0 - 0	7	9.65	59.72
0	0	0 - 0	8	0.00	73.85
0	0	0 - 0	9	1.86	113.31
0	0	0 - 0	10	3.89	149.44
0	0	0 - 0	11	43.84	34.49
0	0	0 - 0	12	20.63	43.87
1	0	1 - 0	1	119.47	182.53
1	0	1 - 0	2	43.00	86.13
1	0	1 - 0	3	59.53	100.10
1	0	1 - 0	4	16.50	36.14
1	0	1 - 0	5	43.52	50.89
1	0	1 - 0	6	7.00	19.37
1	0	1 - 0	7	9.01	53.18
1	0	1 - 0	8	0.00	81.54
1	0	1 - 0	9	0.22	111.60
1	0	1 - 0	10	4.91	114.60
1	0	1 - 0	11	45.46	36.81
1	0	1 - 0	12	17.89	37.39
10	1	10 - 1	1	144.45	175.20
10	1	10 - 1	2	34.27	95.24
10	1	10 - 1	3	52.22	100.69
10	1	10 - 1	4	9.13	27.07
10	1	10 - 1	5	56.12	50.27
10	1	10 - 1	6	4.88	16.19
10	1	10 - 1	7	10.35	58.70
10	1	10 - 1	8	0.00	51.45
10	1	10 - 1	9	0.00	106.00
10	1	10 - 1	10	3.43	115.24
10	1	10 - 1	11	48.20	22.77
10	1	10 - 1	12	23.69	35.35
10	4	10 - 4	1	147.99	193.33
10	4	10 - 4	2	32.00	75.55
10	4	10 - 4	3	62.44	108.54
10	4	10 - 4	4	8.41	33.39
10	4	10 - 4	5	40.03	49.61
10	4	10 - 4	6	8.50	14.21
10	4	10 - 4	7	5.92	63.73
10	4	10 - 4	8	0.00	56.22
10	4	10 - 4	9	2.81	117.86

rate	month	Treatment	month_no	Runoff (mm/ha/month)	Drainage (mm/ha/month)
10	4	10 - 4	10	5.09	138.44
10	4	10 - 4	11	41.62	37.60
10	4	10 - 4	12	13.89	19.29
10	8	10 - 8	1	128.34	182.43
10	8	10 - 8	2	52.31	75.46
10	8	10 - 8	3	52.59	74.85
10	8	10 - 8	4	9.21	32.42
10	8	10 - 8	5	46.29	37.52
10	8	10 - 8	6	8.69	13.98
10	8	10 - 8	7	8.12	61.30
10	8	10 - 8	8	0.00	74.75
10	8	10 - 8	9	2.24	103.36
10	8	10 - 8	10	4.71	119.81
10	8	10 - 8	11	53.11	23.99
10	8	10 - 8	12	8.00	32.34
15	11	15 - 11	1	142.64	182.88
15	11	15 - 11	2	25.82	73.63
15	11	15 - 11	3	55.58	81.00
15	11	15 - 11	4	10.44	36.86
15	11	15 - 11	5	37.24	51.66
15	11	15 - 11	6	3.06	13.02
15	11	15 - 11	7	13.48	52.77
15	11	15 - 11	8	0.00	57.76
15	11	15 - 11	9	2.26	126.96
15	11	15 - 11	10	5.87	136.84
15	11	15 - 11	11	52.91	34.20
15	11	15 - 11	12	13.65	34.88
25	1	25 - 1	1	159.53	189.07
25	1	25 - 1	2	27.28	88.37
25	1	25 - 1	3	52.63	102.06
25	1	25 - 1	4	11.25	29.40
25	1	25 - 1	5	43.55	46.69
25	1	25 - 1	6	12.10	26.24
25	1	25 - 1	7	9.19	57.75
25	1	25 - 1	8	0.00	67.03
25	1	25 - 1	9	0.00	123.94
25	1	25 - 1	10	4.27	146.64
25	1	25 - 1	11	51.00	35.24
25	1	25 - 1	12	16.97	30.73
25	4	25 - 4	1	136.32	185.06
25	4	25 - 4	2	40.49	100.29
25	4	25 - 4	3	60.49	98.49
25	4	25 - 4	4	9.96	51.32
25	4	25 - 4	5	41.66	61.07
25	4	25 - 4	6	10.59	14.43

rate	month	Treatment	month_no	Runoff (mm/ha/month)	Drainage (mm/ha/month)
25	4	25 - 4	7	13.30	61.04
25	4	25 - 4	8	0.00	55.82
25	4	25 - 4	9	0.00	123.11
25	4	25 - 4	10	2.78	134.26
25	4	25 - 4	11	46.49	48.36
25	4	25 - 4	12	11.39	29.22
25	8	25 - 8	1	136.79	174.35
25	8	25 - 8	2	38.90	79.65
25	8	25 - 8	3	63.40	89.97
25	8	25 - 8	4	16.88	34.41
25	8	25 - 8	5	35.83	55.12
25	8	25 - 8	6	16.76	17.18
25	8	25 - 8	7	10.11	73.29
25	8	25 - 8	8	0.00	71.43
25	8	25 - 8	9	0.00	121.06
25	8	25 - 8	10	5.42	140.89
25	8	25 - 8	11	50.00	38.91
25	8	25 - 8	12	19.46	34.30
50	1	50 - 1	1	123.54	176.78
50	1	50 - 1	2	41.03	82.13
50	1	50 - 1	3	55.11	81.84
50	1	50 - 1	4	8.66	38.05
50	1	50 - 1	5	47.86	43.16
50	1	50 - 1	6	14.92	16.83
50	1	50 - 1	7	6.83	52.20
50	1	50 - 1	8	0.00	61.84
50	1	50 - 1	9	0.00	110.58
50	1	50 - 1	10	4.31	139.35
50	1	50 - 1	11	44.99	32.37
50	1	50 - 1	12	11.73	32.26
50	4	50 - 4	1	131.73	187.03
50	4	50 - 4	2	35.71	68.56
50	4	50 - 4	3	57.25	106.94
50	4	50 - 4	4	11.28	33.24
50	4	50 - 4	5	49.90	42.82
50	4	50 - 4	6	7.69	16.96
50	4	50 - 4	7	8.13	56.21
50	4	50 - 4	8	0.00	74.21
50	4	50 - 4	9	2.16	129.23
50	4	50 - 4	10	4.21	137.95
50	4	50 - 4	11	43.75	27.64
50	4	50 - 4	12	19.75	32.27
50	8	50 - 8	1	139.34	183.54
50	8	50 - 8	2	27.75	102.82
50	8	50 - 8	3	52.61	90.50

rate	month	Treatment	month_no	Runoff (mm/ha/month)	Drainage (mm/ha/month)
50	8	50 - 8	4	11.65	26.75
50	8	50 - 8	5	50.86	42.07
50	8	50 - 8	6	12.58	14.87
50	8	50 - 8	7	10.64	67.22
50	8	50 - 8	8	0.00	61.67
50	8	50 - 8	9	0.00	102.57
50	8	50 - 8	10	8.05	141.90
50	8	50 - 8	11	42.19	21.11
50	8	50 - 8	12	19.53	36.22
75	1	75 - 1	1	145.05	191.77
75	1	75 - 1	2	23.55	80.61
75	1	75 - 1	3	60.30	103.96
75	1	75 - 1	4	12.39	35.23
75	1	75 - 1	5	43.46	52.19
75	1	75 - 1	6	9.70	16.55
75	1	75 - 1	7	8.30	46.32
75	1	75 - 1	8	0.00	75.42
75	1	75 - 1	9	0.00	111.96
75	1	75 - 1	10	2.18	138.98
75	1	75 - 1	11	40.30	38.55
75	1	75 - 1	12	16.95	27.47
75	4	75 - 4	1	117.36	178.41
75	4	75 - 4	2	42.85	74.31
75	4	75 - 4	3	53.78	81.19
75	4	75 - 4	4	12.16	43.17
75	4	75 - 4	5	49.40	60.32
75	4	75 - 4	6	12.11	17.89
75	4	75 - 4	7	9.84	53.33
75	4	75 - 4	8	0.00	77.11
75	4	75 - 4	9	1.65	135.25
75	4	75 - 4	10	2.91	155.88
75	4	75 - 4	11	48.73	26.94
75	4	75 - 4	12	11.49	26.63
75	8	75 - 8	1	135.26	180.66
75	8	75 - 8	2	28.16	83.09
75	8	75 - 8	3	55.81	96.18
75	8	75 - 8	4	11.43	43.16
75	8	75 - 8	5	44.50	62.05
75	8	75 - 8	6	6.54	12.63
75	8	75 - 8	7	13.78	48.21
75	8	75 - 8	8	0.00	63.58
75	8	75 - 8	9	3.15	117.79
75	8	75 - 8	10	4.41	124.95
75	8	75 - 8	11	44.91	44.10
75	8	75 - 8	12	14.14	36.19

rate	month	Treatment	month_no	Runoff (mm/ha/month)	Drainage (mm/ha/month)
100	1	100 - 1	1	142.56	180.55
100	1	100 - 1	2	46.89	81.84
100	1	100 - 1	3	53.18	103.72
100	1	100 - 1	4	12.42	39.95
100	1	100 - 1	5	31.13	42.01
100	1	100 - 1	6	13.67	19.31
100	1	100 - 1	7	9.09	64.55
100	1	100 - 1	8	0.00	49.54
100	1	100 - 1	9	4.52	114.68
100	1	100 - 1	10	4.89	104.39
100	1	100 - 1	11	46.93	30.27
100	1	100 - 1	12	18.92	29.10
100	4	100 - 4	1	129.19	176.60
100	4	100 - 4	2	22.54	56.38
100	4	100 - 4	3	59.65	106.21
100	4	100 - 4	4	7.53	34.55
100	4	100 - 4	5	31.11	51.15
100	4	100 - 4	6	8.22	18.22
100	4	100 - 4	7	9.82	54.66
100	4	100 - 4	8	0.00	71.47
100	4	100 - 4	9	0.00	116.88
100	4	100 - 4	10	2.98	120.40
100	4	100 - 4	11	44.31	28.18
100	4	100 - 4	12	18.04	31.32
100	8	100 - 8	1	157.60	203.96
100	8	100 - 8	2	27.71	91.05
100	8	100 - 8	3	54.76	96.61
100	8	100 - 8	4	9.93	44.72
100	8	100 - 8	5	37.03	56.71
100	8	100 - 8	6	3.86	15.81
100	8	100 - 8	7	5.27	54.51
100	8	100 - 8	8	0.00	72.28
100	8	100 - 8	9	0.00	114.54
100	8	100 - 8	10	5.09	143.09
100	8	100 - 8	11	43.15	28.26
100	8	100 - 8	12	10.77	32.66

Appendix N. Analysis of Variance and Multiple Comparisons–: Runoff Totals for Cations for All Treatments

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

Short Output:
Call:
   aov(formula = na ~ rate * month, data = runoff.totals, na.action = na.omit)

Terms:
                   rate   month rate:month Residuals
 Sum of Squares   26589    5412      16478   1247095
Deg. of Freedom       7       2          8       342

Residual standard error: 60.38606
22 out of 40 effects not estimable
Estimated effects may be unbalanced

            Df Sum of Sq  Mean Sq  F Value     Pr(F)
      rate   7     26589 3798.472 1.041683 0.4015525
     month   2      5412 2705.915 0.742063 0.4768956
rate:month   8     16478 2059.781 0.564869 0.8065651
 Residuals 342   1247095 3646.476
```

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

Short Output:
Call:
   aov(formula = k ~ rate * month, data = runoff.totals, na.action = na.omit)

Terms:
                   rate    month rate:month Residuals
 Sum of Squares 688.344   21.587     50.341  3660.126
Deg. of Freedom       7        2          8       342

Residual standard error: 3.27141
22 out of 40 effects not estimable
Estimated effects may be unbalanced

            Df Sum of Sq  Mean Sq  F Value     Pr(F)
      rate   7   688.344 98.33484 9.188348 0.0000000
     month   2    21.587 10.79341 1.008530 0.3658370
rate:month   8    50.341  6.29265 0.587981 0.7878026
 Residuals 342  3660.126 10.70212


95 % simultaneous confidence intervals for specified
linear combinations, by the Sidak method

critical point: 3.1398
response variable: rate

intervals excluding 0 are flagged by '****'

       Estimate Std.Error Lower Bound Upper Bound
   0-1   0.4630     0.517      -1.160     2.09000
   0-6   0.2100     0.291      -0.703     1.12000
  0-10  -1.2700     0.408      -2.550     0.00865
  0-25  -0.3480     0.408      -1.630     0.93200
  0-50   0.3890     0.408      -0.891     1.67000
  0-75   0.9920     0.408      -0.288     2.27000
 0-100   3.9300     0.465       2.470     5.39000 ****
   1-6  -0.2530     0.291      -1.170     0.66000
  1-10  -1.7300     0.408      -3.010    -0.45400 ****
  1-25  -0.8110     0.408      -2.090     0.46900
  1-50  -0.0738     0.408      -1.350     1.21000
  1-75   0.5290     0.408      -0.751     1.81000
```

```
 1-100   3.4600     0.465       2.000      4.92000 ****
  6-10  -1.4800     0.288      -2.390     -0.57500 ****
  6-25  -0.5580     0.288      -1.460      0.34800
  6-50   0.1790     0.288      -0.727      1.08000
  6-75   0.7820     0.288      -0.124      1.69000
 6-100   3.7200     0.375       2.540      4.89000 ****
 10-25   0.9230     0.448      -0.483      2.33000
 10-50   1.6600     0.448       0.253      3.07000 ****
 10-75   2.2600     0.448       0.856      3.67000 ****
10-100   5.2000     0.453       3.780      6.62000 ****
 25-50   0.7370     0.448      -0.670      2.14000
 25-75   1.3400     0.448      -0.067      2.75000
25-100   4.2700     0.453       2.850      5.70000 ****
 50-75   0.6030     0.448      -0.804      2.01000
50-100   3.5400     0.453       2.120      4.96000 ****
75-100   2.9300     0.453       1.510      4.36000 ****
```

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

Short Output:
Call:
   aov(formula = ca ~ rate * month, data = runoff.totals, na.action = na.omit)

Terms:
                      rate    month rate:month Residuals
 Sum of Squares     87.198    2.607     24.158  1762.451
Deg. of Freedom          7        2          8       342

Residual standard error: 2.270102
22 out of 40 effects not estimable
Estimated effects may be unbalanced

            Df Sum of Sq  Mean Sq  F Value     Pr(F)
      rate   7    87.198 12.45690 2.417237 0.0199049
     month   2     2.607  1.30371 0.252981 0.7766274
rate:month   8    24.158  3.01974 0.585975 0.7894507
 Residuals 342  1762.451  5.15336


95 % simultaneous confidence intervals for specified
linear combinations, by the Sidak method

critical point: 3.1398
response variable: rate

intervals excluding 0 are flagged by '****'

       Estimate Std.Error Lower Bound Upper Bound
   0-1  0.02080     0.359      -1.110       1.150
   0-6 -0.12000     0.202      -0.754       0.513
  0-10 -0.63700     0.283      -1.520       0.251
  0-25 -0.48400     0.283      -1.370       0.404
  0-50 -0.18600     0.283      -1.070       0.702
  0-75  0.02290     0.283      -0.865       0.911
 0-100  1.59000     0.323       0.580       2.610 ****
   1-6 -0.14100     0.202      -0.775       0.492
  1-10 -0.65800     0.283      -1.550       0.230
  1-25 -0.50500     0.283      -1.390       0.383
  1-50 -0.20600     0.283      -1.090       0.682
  1-75  0.00209     0.283      -0.886       0.890
 1-100  1.57000     0.323       0.559       2.590 ****
  6-10 -0.51600     0.200      -1.140       0.112
  6-25 -0.36300     0.200      -0.992       0.265
  6-50 -0.06510     0.200      -0.694       0.563
  6-75  0.14300     0.200      -0.485       0.772
```

```
  6-100  1.71000     0.260       0.898       2.530 ****
 10-25   0.15300     0.311      -0.823       1.130
 10-50   0.45100     0.311      -0.525       1.430
 10-75   0.66000     0.311      -0.316       1.640
10-100   2.23000     0.314       1.240       3.220 ****
 25-50   0.29800     0.311      -0.678       1.270
 25-75   0.50700     0.311      -0.469       1.480
25-100   2.08000     0.314       1.090       3.060 ****
 50-75   0.20900     0.311      -0.767       1.180
50-100   1.78000     0.314       0.793       2.770 ****
75-100   1.57000     0.314       0.584       2.560 ****
```

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

Short Output:
Call:
   aov(formula = mg ~ rate * month, data = runoff.totals, na.action = na.omit)

Terms:
                     rate    month rate:month Residuals
 Sum of Squares   760.994   28.683     21.979  2255.448
Deg. of Freedom         7        2          8       342

Residual standard error: 2.568049
22 out of 40 effects not estimable
Estimated effects may be unbalanced

            Df Sum of Sq  Mean Sq  F Value      Pr(F)
      rate   7   760.994 108.7134 16.48452 0.0000000
     month   2    28.683  14.3413  2.17461 0.1152213
rate:month   8    21.979   2.7474  0.41659 0.9108369
 Residuals 342  2255.448   6.5949

95 % simultaneous confidence intervals for specified
linear combinations, by the Sidak method

critical point: 3.1398
response variable: rate

intervals excluding 0 are flagged by '****'

       Estimate Std.Error Lower Bound Upper Bound
   0-1   0.3770     0.406     -0.8980      1.6500
   0-6   0.4840     0.228     -0.2330      1.2000
  0-10  -0.6810     0.320     -1.6900      0.3240
  0-25   0.2850     0.320     -0.7190      1.2900
  0-50   1.0400     0.320      0.0384      2.0500 ****
  0-75   1.4100     0.320      0.4030      2.4100 ****
 0-100   3.4800     0.365      2.3300      4.6200 ****
   1-6   0.1070     0.228     -0.6100      0.8230
  1-10  -1.0600     0.320     -2.0600     -0.0532 ****
  1-25  -0.0916     0.320     -1.1000      0.9130
  1-50   0.6660     0.320     -0.3390      1.6700
  1-75   1.0300     0.320      0.0261      2.0400 ****
 1-100   3.1000     0.365      1.9500      4.2500 ****
  6-10  -1.1600     0.226     -1.8800     -0.4540 ****
  6-25  -0.1980     0.226     -0.9090      0.5130
  6-50   0.5590     0.226     -0.1520      1.2700
  6-75   0.9240     0.226      0.2130      1.6300 ****
 6-100   2.9900     0.294      2.0700      3.9200 ****
 10-25   0.9660     0.352     -0.1380      2.0700
 10-50   1.7200     0.352      0.6200      2.8300 ****
 10-75   2.0900     0.352      0.9840      3.1900 ****
10-100   4.1600     0.355      3.0400      5.2700 ****
```

```
 25-50   0.7580     0.352     -0.3470       1.8600
 25-75   1.1200     0.352      0.0182       2.2300  ****
25-100   3.1900     0.355      2.0800       4.3100  ****
 50-75   0.3650     0.352     -0.7390       1.4700
50-100   2.4300     0.355      1.3200       3.5500  ****
75-100   2.0700     0.355      0.9540       3.1900  ****
```

Appendix O. Analysis of Variance and Multiple Comparisons–: Nitrogen and Phosphorus in Runoff for All Treatments

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

Short Output:
Call:
   aov(formula = inorgn ~ rate * month, data = runoff.np, na.action =
      na.omit)

Terms:
                    rate    month rate:month Residuals
 Sum of Squares 10087134   641642     184739   1810988
Deg. of Freedom        7        2          8       342

Residual standard error: 72.76872
22 out of 40 effects not estimable
Estimated effects may be unbalanced

            Df Sum of Sq Mean Sq  F Value         Pr(F)
      rate   7  10087134 1441019 272.1324 0.00000000000
     month   2    641642  320821  60.5862 0.00000000000
rate:month   8    184739   23092   4.3609 0.00004985194
 Residuals 342   1810988    5295


95 % simultaneous confidence intervals for specified
linear combinations, by the Sidak method

critical point: 3.1398
response variable: rate

intervals excluding 0 are flagged by '****'

       Estimate Std.Error Lower Bound Upper Bound
   0-1   -26.80     11.50       -63.0        9.28
  0-10    47.50      9.07        19.1       76.00 ****
  0-15   -38.40      6.47       -58.8      -18.10 ****
  0-25    -6.68      9.07       -35.2       21.80
  0-50   -97.90      9.07      -126.0      -69.40 ****
  0-75  -200.00      9.07      -228.0     -171.00 ****
 0-100  -287.00     10.30      -320.0     -255.00 ****
  1-10    74.40      9.07        45.9      103.00 ****
  1-15   -11.60      6.47       -31.9        8.71
  1-25    20.20      9.07        -8.3       48.60
  1-50   -71.00      9.07       -99.5      -42.60 ****
  1-75  -173.00      9.07      -201.0     -144.00 ****
 1-100  -261.00     10.30      -293.0     -228.00 ****
 10-15   -86.00      6.42      -106.0      -65.80 ****
 10-25   -54.20      9.96       -85.5      -22.90 ****
 10-50  -145.00      9.96      -177.0     -114.00 ****
 10-75  -247.00      9.96      -278.0     -216.00 ****
10-100  -335.00     10.10      -367.0     -303.00 ****
 15-25    31.80      6.42        11.6       51.90 ****
 15-50   -59.40      6.42       -79.6      -39.30 ****
 15-75  -161.00      6.42      -181.0     -141.00 ****
15-100  -249.00      8.33      -275.0     -223.00 ****
 25-50   -91.20      9.96      -122.0      -59.90 ****
 25-75  -193.00      9.96      -224.0     -162.00 ****
25-100  -281.00     10.10      -312.0     -249.00 ****
 50-75  -102.00      9.96      -133.0      -70.40 ****
50-100  -189.00     10.10      -221.0     -158.00 ****
75-100   -87.80     10.10      -119.0      -56.10 ****
```

```
95 % simultaneous confidence intervals for specified
linear combinations, by the Sidak method

critical point: 2.817
response variable: rate

intervals excluding 0 are flagged by '****'

     Estimate Std.Error Lower Bound Upper Bound
 0-1   -37.00      8.35       -60.6       -13.5 ****
 0-4  -119.00      8.35      -143.0       -95.5 ****
 0-8  -127.00      8.35      -150.0      -103.0 ****
0-11    72.80     10.60        42.8       103.0 ****
 1-4   -82.00      9.64      -109.0       -54.8 ****
 1-8   -89.50      9.64      -117.0       -62.3 ****
1-11   110.00     10.60        80.1       140.0 ****
 4-8    -7.55      9.64       -34.7        19.6
4-11   192.00     10.60       162.0       222.0 ****
8-11   199.00     10.60       170.0       229.0 ****
```

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

Short Output:
Call:
   aov(formula = orgn ~ rate * month, data = runoff.np, na.action =
       na.omit)

Terms:
                     rate    month rate:month Residuals
 Sum of Squares    4.2939   1.9647     6.8646  186.2143
Deg. of Freedom         7        2          8       342

Residual standard error: 0.7378931
22 out of 40 effects not estimable
Estimated effects may be unbalanced

            Df Sum of Sq   Mean Sq  F Value     Pr(F)
      rate   7    4.2939 0.6134193 1.126602 0.3456963
     month   2    1.9647 0.9823318 1.804144 0.1661784
rate:month   8    6.8646 0.8580800 1.575944 0.1306932
 Residuals 342  186.2143 0.5444863
```

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

Short Output:
Call:
   aov(formula = orthop ~ rate * month, data = runoff.np, na.action =
       na.omit)

Terms:
                    rate    month rate:month Residuals
 Sum of Squares   815.49    77.62     874.70  43875.53
Deg. of Freedom        7        2          8       342

Residual standard error: 11.32656
22 out of 40 effects not estimable
Estimated effects may be unbalanced

             Df Sum of Sq  Mean Sq   F Value     Pr(F)
      rate    7    815.49 116.4980 0.9080764 0.5001987
     month    2     77.62  38.8114 0.3025265 0.7391465
rate:month    8    874.70 109.3373 0.8522601 0.5572657
 Residuals 342  43875.53 128.2910
```

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

Short Output:
Call:
   aov(formula = orgp ~ rate * month, data = runoff.np, na.action =
       na.omit)

Terms:
                    rate    month rate:month Residuals
 Sum of Squares  15.2297   1.3613    16.2585  786.4603
Deg. of Freedom        7        2          8       342

Residual standard error: 1.51644
22 out of 40 effects not estimable
Estimated effects may be unbalanced

             Df Sum of Sq  Mean Sq   F Value     Pr(F)
      rate    7   15.2297 2.175673 0.9461128 0.4708844
     month    2    1.3613 0.680635 0.2959806 0.7439922
rate:month    8   16.2585 2.032310 0.8837701 0.5302585
 Residuals 342  786.4603 2.299591
```

Appendix P. Analysis of Variance and Multiple Comparisons–: Drainage Totals for Cations and Inorganic Nitrogen for All Treatments

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

Short Output:
Call:
   aov(formula = na ~ rate * month, data = drain.totals,
       na.action = na.omit)

Terms:
                   rate   month rate:month Residuals
 Sum of Squares  137312  103587      69911   5928570
Deg. of Freedom       7       2          8       342

Residual standard error: 131.6624
22 out of 40 effects not estimable
Estimated effects may be unbalanced

            Df Sum of Sq  Mean Sq  F Value     Pr(F)
      rate   7    137312 19615.95 1.131581 0.3425972
     month   2    103587 51793.46 2.987797 0.0517156
rate:month   8     69911  8738.93 0.504121 0.8530935
 Residuals 342   5928570 17335.00
```

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

Short Output:
Call:
   aov(formula = k ~ rate * month, data = drain.totals,
       na.action = na.omit)

Terms:
                   rate    month rate:month Residuals
 Sum of Squares  0.44801  0.40686    1.49332  29.66807
Deg. of Freedom        7        2          8       342

Residual standard error: 0.2945314
22 out of 40 effects not estimable
Estimated effects may be unbalanced

            Df Sum of Sq   Mean Sq  F Value     Pr(F)
      rate   7   0.44801 0.0640014 0.737779 0.6400562
     month   2   0.40686 0.2034303 2.345052 0.0973816
rate:month   8   1.49332 0.1866645 2.151783 0.0307250
 Residuals 342  29.66807 0.0867487
```

Appendix P: Analysis of Variance and Multiple Comparisons–: Drainage Totals for Cations and Inorganic Nitrogen for All Treatments

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

Short Output:
Call:
   aov(formula = ca ~ rate * month, data = drain.totals,
       na.action = na.omit)

Terms:
                   rate    month rate:month Residuals
 Sum of Squares  36.104    3.396     32.524  1750.967
Deg. of Freedom       7        2          8       342

Residual standard error: 2.262695
22 out of 40 effects not estimable
Estimated effects may be unbalanced

            Df Sum of Sq  Mean Sq  F Value     Pr(F)
      rate   7    36.104 5.157780 1.007421 0.4256538
     month   2     3.396 1.697872 0.331629 0.7179838
rate:month   8    32.524 4.065475 0.794071 0.6081690
 Residuals 342  1750.967 5.119787
```

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

Short Output:
Call:
   aov(formula = mg ~ rate * month, data = drain.totals,
       na.action = na.omit)

Terms:
                   rate    month rate:month Residuals
 Sum of Squares 145.656   14.625    128.772  6996.794
Deg. of Freedom       7        2          8       342

Residual standard error: 4.523103
22 out of 40 effects not estimable
Estimated effects may be unbalanced

            Df Sum of Sq  Mean Sq  F Value     Pr(F)
      rate   7   145.656 20.80806 1.017088 0.4187653
     month   2    14.625  7.31231 0.357422 0.6997381
rate:month   8   128.772 16.09644 0.786786 0.6146080
 Residuals 342  6996.794 20.45846
```

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

Short Output:
Call:
   aov(formula = n ~ rate * month, data = drain.totals,
       na.action = na.omit)

Terms:
                    rate    month rate:month Residuals
 Sum of Squares 27935950  1080847    1456590   6838910
Deg. of Freedom        7        2          8       342

Residual standard error: 141.4101
22 out of 40 effects not estimable
Estimated effects may be unbalanced

            Df Sum of Sq Mean Sq  F Value
      rate   7  27935950 3990850 199.5743
     month   2   1080847  540423  27.0255
rate:month   8   1456590  182074   9.1051
 Residuals 342   6838910   19997
                    Pr(F)
      rate 0.000000e+000
     month 1.267753e-011
rate:month 2.323519e-011
 Residuals


95 % simultaneous confidence intervals for specified
linear combinations, by the Sidak method

critical point: 3.1398
response variable: rate

intervals excluding 0 are flagged by '****'

       Estimate Std.Error Lower Bound Upper Bound
   0-1   -33.00      22.4     -103.00       37.20
  0-10    60.40      17.6        5.06      116.00 ****
  0-15   -37.60      12.6      -77.10        1.83
  0-25    34.00      17.6      -21.30       89.30
  0-50   -58.10      17.6     -113.00       -2.82 ****
  0-75  -278.00      17.6     -333.00     -222.00 ****
 0-100  -511.00      20.1     -574.00     -448.00 ****
  1-10    93.40      17.6       38.10      149.00 ****
  1-15    -4.62      12.6      -44.10       34.80
  1-25    67.00      17.6       11.70      122.00 ****
  1-50   -25.10      17.6      -80.40       30.20
  1-75  -245.00      17.6     -300.00     -189.00 ****
 1-100  -478.00      20.1     -541.00     -415.00 ****
 10-15   -98.00      12.5     -137.00      -58.90 ****
 10-25   -26.40      19.4      -87.20       34.40
 10-50  -119.00      19.4     -179.00      -57.70 ****
 10-75  -338.00      19.4     -399.00     -277.00 ****
10-100  -571.00      19.6     -633.00     -510.00 ****
 15-25    71.60      12.5       32.50      111.00 ****
 15-50   -20.50      12.5      -59.70       18.60
 15-75  -240.00      12.5     -279.00     -201.00 ****
15-100  -473.00      16.2     -524.00     -422.00 ****
 25-50   -92.10      19.4     -153.00      -31.30 ****
 25-75  -312.00      19.4     -372.00     -251.00 ****
25-100  -545.00      19.6     -606.00     -483.00 ****
 50-75  -220.00      19.4     -280.00     -159.00 ****
50-100  -453.00      19.6     -514.00     -391.00 ****
75-100  -233.00      19.6     -295.00     -172.00 ****
```