Chapter 4. In four of these studies various split applications of fertilizer were made or fertilizer application was delayed some time after planting.

In one of these studies (Storrier, 1965), no yield response to a late split application of fertilizer was obtained. In the experiments of Christensen and Killorn (1981) at Bozeman, Montana, ammonium nitrate fertilizer was broadcast on the soil surface shortly after planting or at the heading or flowering growth stages. In this experiment (see Figure 4.3) some response to timing was evident. The simulated response was less than that observed but still within the standard error of the observations.

The experiment of Mason et al. (1972) at Lancelin in Western Australia is the only one in the model validation data base where a positive response to a delayed application was evident. In this experiment conducted on a coarse sand, urea was applied at planting or at 2, 4, or 8 weeks after planting. The later the application was made, the less N was lost to leaching, the higher was the recovery of N by the crop and the grain yield. The model was able to capture this almost threefold response to timing in this very low-yielding environment.

To test further the sensitivity of the model to fertilizer management strategies, a simulation experiment using some of the Lancelin data was conducted. The model was run with the single season of Lancelin weather data and the same soil properties as cited in Mason et al. (1972). Genetic coefficients, appropriate for the variety as used in the validation simulation, were used, as was the reported planting date. The following management options were explored:

(a) Rates of N

0, 30, 60, 90, 120, 180, and 270 kg N/ha

(b) Splitting strategies

100/0, 75/25, 50/50, 25/75, and 0/100

In the above expressed as A/B, A refers to the proportion of the rate applied at planting and B refers to the proportion of the rate applied in the second application.

(c) Time of second application

0, 15, 30, 45, 60, 75, and 90 days after planting.

The amount of N as nitrate leaching from the bottom of the profile (layer 90 cm deep) and the grain yield from each of these simulations are plotted (Figures 6.3 and 6.4, respectively).

In an environment such as this where leaching is very extensive there is great sensitivity to fertilizer management. There is a large response to fertilizer except in the case where all the fertilizer was applied at planting (Figure 6.4). In this case large losses of N from the profile occur (Figure 6.3). As the applications are progressively delayed the amount of N leached from the bottom of the profile declines and yield increases. Disposition of nitrate from the upper part of the profile still occurs with the late applications but loss from the profile (Figure 6.5) is reduced. If the majority of the fertilizer is not applied until 90 days after planting yield reductions occur due to early N stress and the subsequent inability of the crop to utilize fertilizer N effectively. Applying some of the fertilizer at planting helps to alleviate some of this stress.

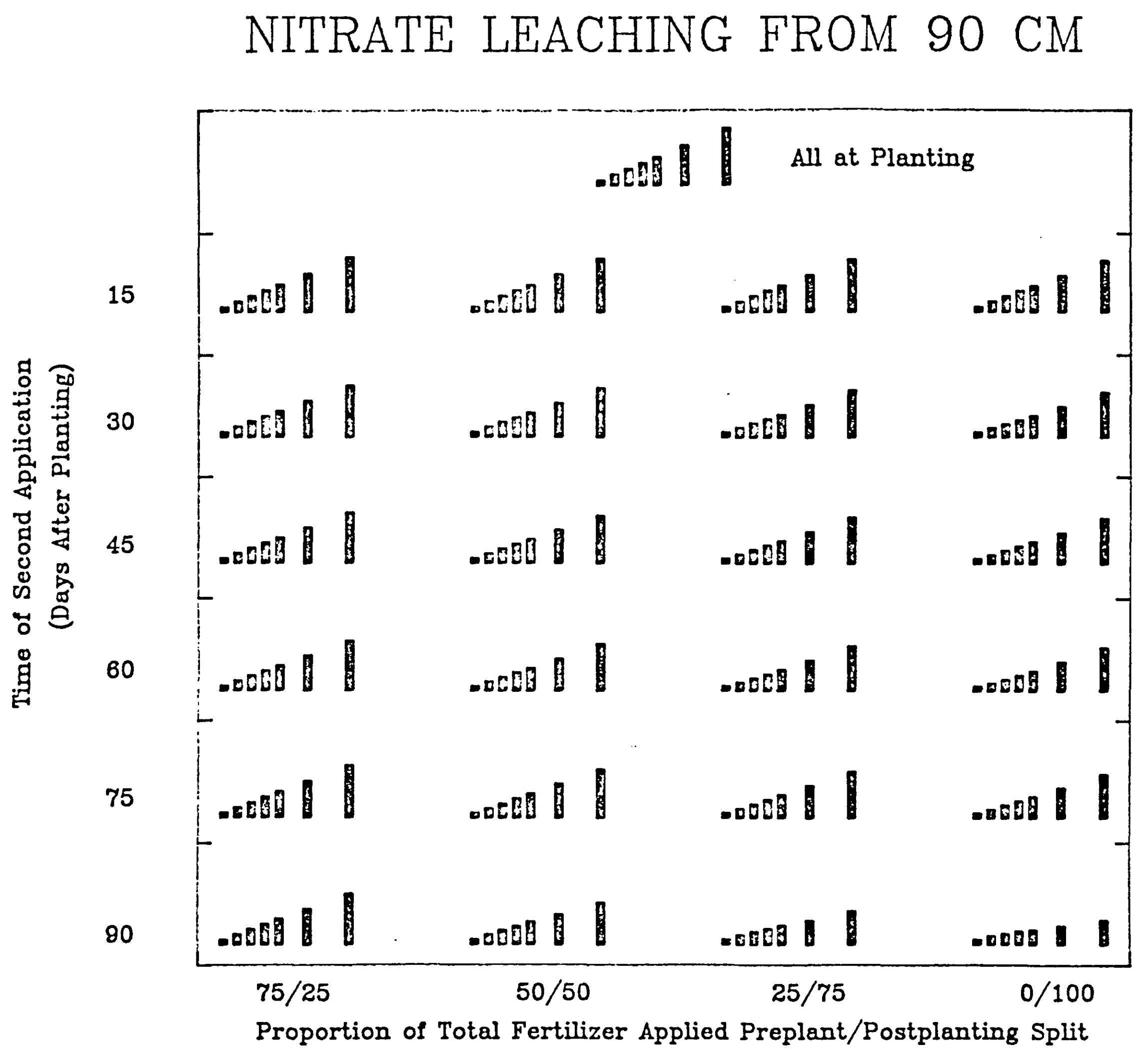

Figure 6.3. Simulated Nitrate Losses From the Bottom of the Soil Profile at Lancelin. Each Column Represents a Nitrogen Rate (Total N Applied). Thus Each Group of Columns Represents the Seven N Rates (0, 30, 60, 90, 120, 180, and 270 kg N/ha). Relative Magnitudes of Leaching Losses Can Be Grouped From the Column Heights. The 100/0 (Preplant/Postplant Split) Application Treatment Is Indicated at the Top of the Figure by "All at Planting."

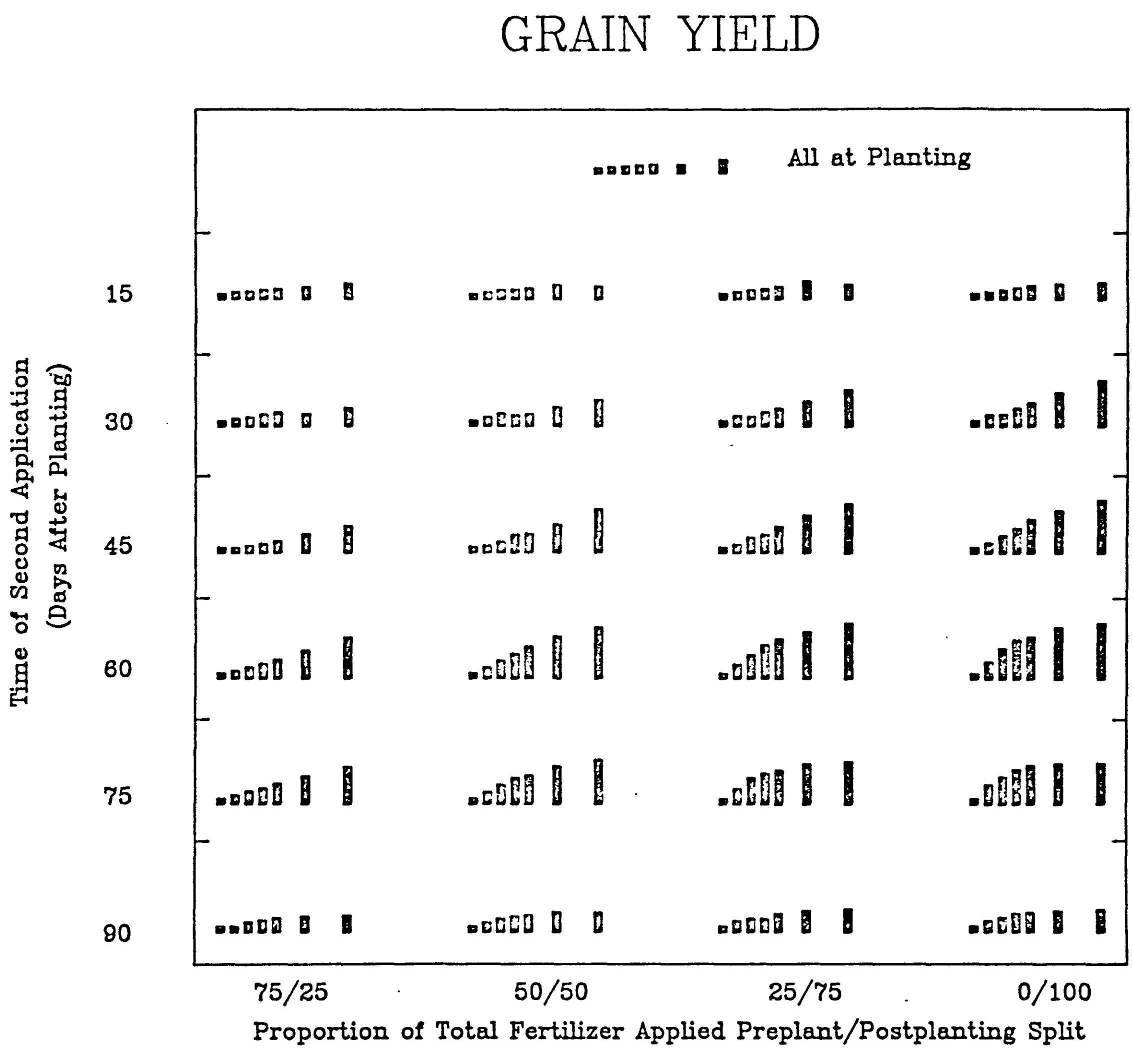

Figure 6.4. Simulated Grain Yield Response to Various Fertilizer Split Application Strategies at Lancelin. Column Representations as in Figure 6.3.

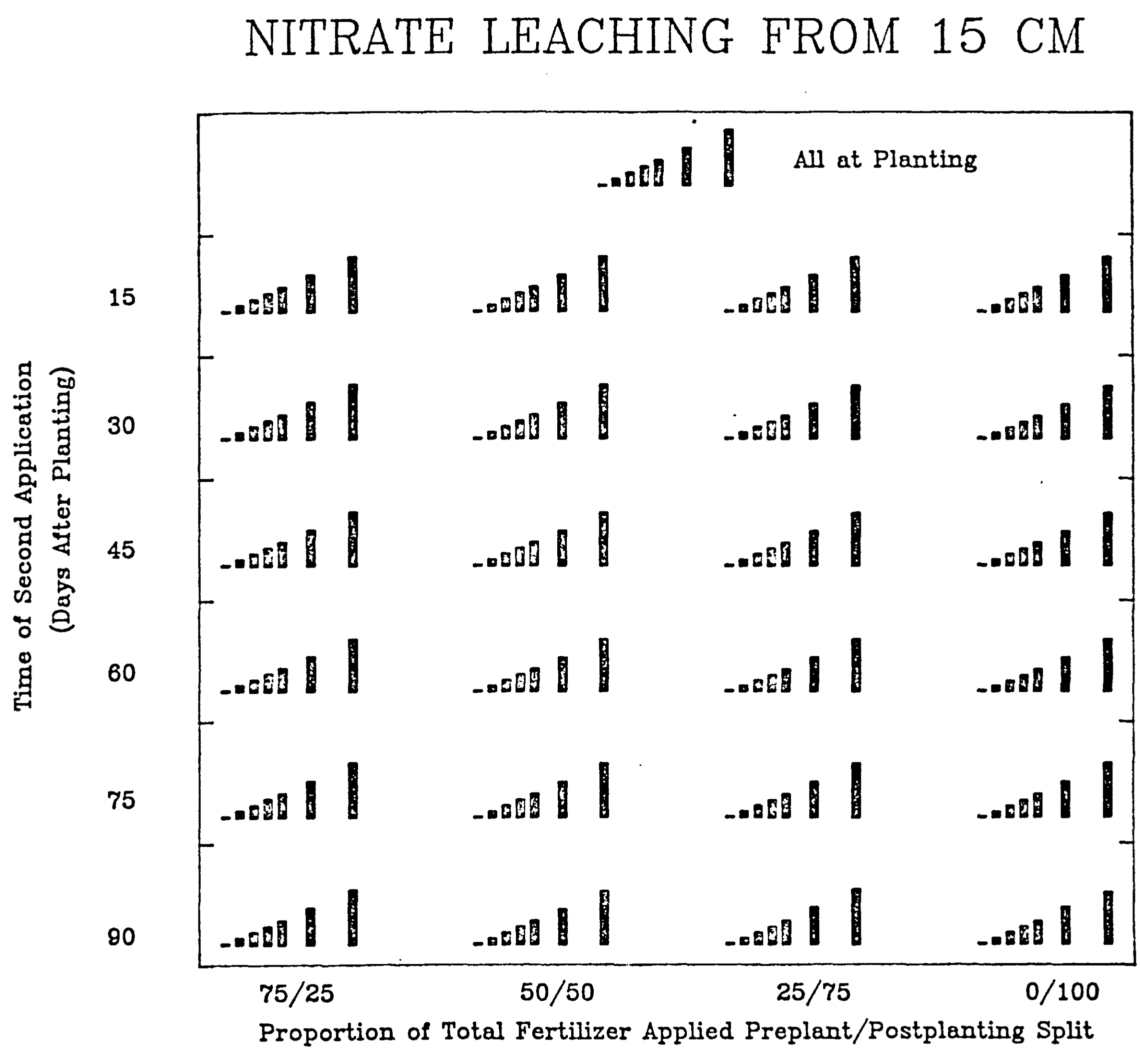

Figure 6.5. Simulated Flux of Nitrate From a Layer 15 cm Deep at Lancelin Under Various Fertilizer Strategies at Lancelin. Column Representations as in Figure 6.3.

To help ascertain an optimum fertilizer timing strategy, a surface can be fitted to simulated yield as a function of time of application and proportion of fertilizer applied at planting. For the 180 kg N/ha rate, this surface suggests an optimum would be to apply approximately 90 kg N/ha at planting and 90 kg N/ha 100 days after planting. Further investigation of the rates and times of leaching and experimentation on rates and timing strategies should yield further insights into appropriate fertilizer strategies for this environment. The simulated response to fertilizer and application timing indicate the model is very sensitive to these parameters where prevailing conditions allow its expression.

6.4. Sensitivity to Soil Physical Properties

Various soil physical properties affect the amount of water a soil can store, the amount of runoff, the rate of drainage, and the distribution of root growth. The soil bulk density, via its effect on soil strength, will affect root growth, since bulk density is used in the calculation of mineral N in units of kilogram of N per hectare from units of N concentration in parts per million or milligram of N per hectare of soil. This calculation will notionally affect the initial soil N supply and N balance calculations.

An examination of the effect of some of the physical properties was reported in Section 6.2 above. Changing the LL and the DUL clearly affects soil water storage and hence crop growth, particularly in the drier areas. Similar but less apparent effects were found when SAT, SWCON, and BD were altered.

To test the sensitivity of the model to soil physical properties, the climatic and soil N data from the experiment of Mason et al. (1972) at Lancelin were again used. Three runs of the model, each with a different set of soil characteristics, were run. The characteristics used were those typical of an Entisol (structureless sand), a Mollisol (loamy texture), and a Vertisol (heavy clay). The soil water input data for the three soils are tabulated (Table 6.7).

When all the fertilizer was applied at planting, less nitrate was leached and the crop less frequently encountered short-term moisture stress as the texture was changed from sand to loam to clay. The differences in simulated grain yield (Figure 6.6) on these three soil types are substantial. When the fertilizer application is split by applying 50% at planting and the remainder 45 days after planting, the losses from the sand are greatly reduced with concomitant large increases in yield (Figure 6.7). Yield increases due to the splitting strategy are also evident on the other two soil types but are less pronounced than on the sand. The exercise clearly illustrates the capability of the model to describe the interaction between soil physical properties and some aspects of fertilizer management, as well as the necessity to accurately describe the parameters describing water-holding capacity and flux through the profile.

6.5 Sensitivity to Depth of Fertilizer Placement

In dry locations the surface soil frequently dries out while there is adequate moisture to maintain plant growth at depth. Since most of the nutrients required by the crop are concentrated in the upper layers of the soil profile, this surface drying leads to a

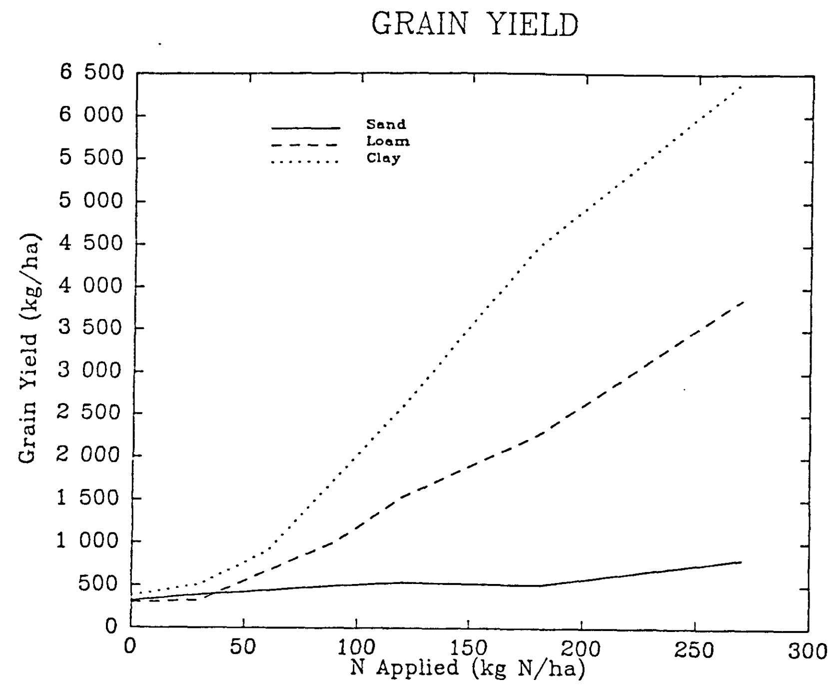

Figure 6.6. Simulated Yield Response to Basal Applications of Fertilizer at Lancelin on Three Soil Types.

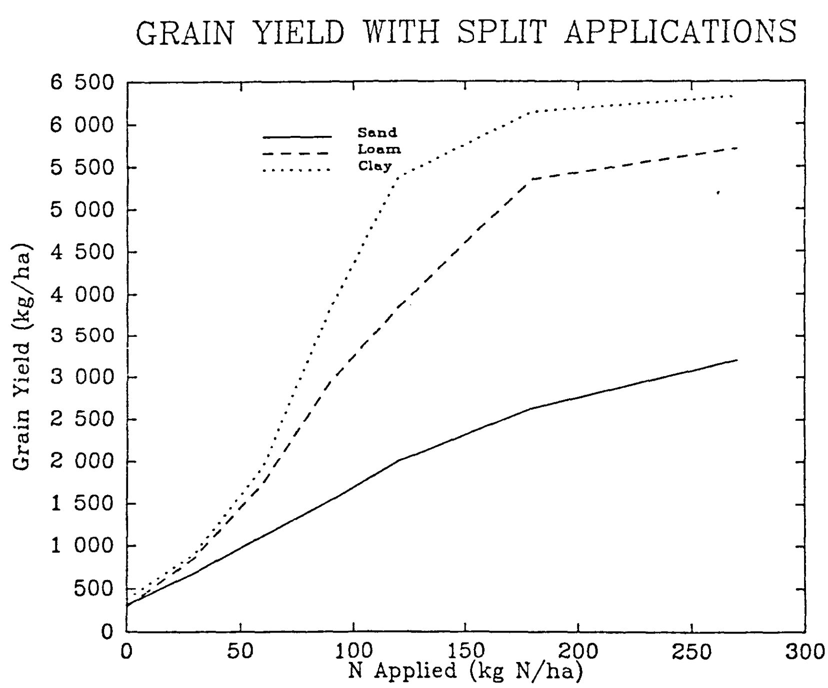

Figure 6.7. Simulated Yield Response to Split Applications of Fertilizer at Lancelin on Three Soil Types.

Table 6.7. Soil Water Input Data Used in Sensitivity Analysis

Layer Depth	Lower Limit	Drained Upper Limit	Saturation
	Sand		
5.000	0.038	0.085	0.300
10.000	0.038	0.085	0.300
15.000	0.038	0.085	0.300
15.000	0.038	0.065	0.300
15.000	0.038	0.065	0.300
15.000	0.038	0.065	0.300
15.000	0.038	0.065	0.300
	Loam		
5.000	0.080	0.210	0.260
10.000	0.090	0.210	0.250
15.000	0.100	0.190	0.230
15.000	0.100	0.190	0.230
15.000	0.130	0.210	0.250
15.000	0.200	0.280	0.310
15.000	0.200	0.280	0.310
	Silty Clay		
5.000	0.215	0.350	0.380
10.000	0.215	0.350	0.400
15.000	0.215	0.350	0.400
15.000	0.215	0.350	0.400
15.000	0.215	0.350	0.400
15.000	0.215	0.350	0.400
15.000	0.215	0.350	0.400

nutritional drought. The argument for deep placement of fertilizer is that the nutrient will be located further down the profile where there is a greater likelihood of adequate moisture being present. The response to depth of fertilizer placement is more likely to be apparent with less mobile nutrients. Simpson and Lipsett (1973) and Simpson et al. (1975) have reported responses to deep placement of phosphatic fertilizer when the surface soil dried out.

Responses to deep placement of nitrogenous fertilizers are not as clearly defined. Alston (1980) was unable to find a significant apparent with less mobile nutrients. Simpson and Lipsett (1973) and Simpson et al. (1975) have reported responses to deep placement of phosphatic fertilizer when the surface soil dried out.

Responses to deep placement of nitrogenous fertilisers are not as clearly defined. Alston (1980) was unable to find a significant response to depth of placement of nitrogenous fertilisers on a red-brown earth in South Australia. Similarly, Daigger and Sander (1976) found no significant difference in response to nitrogenous fertilizer when the fertilizer was placed at either 0, 30, 60, 90, 120, or 150 cm on two soils in western Nebraska. Strong and Cooper (1980), however, were able to demonstrate a significant response by wheat to depth of fertilizer placement on heavy cracking clay soils in southern Queensland. Craswell and Strong (1976), working on a similar soil, reported that deep placement (45 cm) of fertilizer reduced denitrification losses, enhanced N uptake, and increased yield compared to shallow placement (15 cm).

6.5.1 Methods

To test the sensitivity of the model to fertilizer placement, 20-year simulation runs were made using daily generated weather data for a Mediterranean-type climate location (Waite Institute, S.A.) and for a summer rainfall dominant location (Jondaryan, QLD). At the Waite Institute site, periodic droughts during the grain-filling period occur frequently, while at Jondaryan there is a greater likelihood of short-term drought early in the growing season. (See Chapter 5 for details of rainfall distribution and weather generation procedures.)

Input data typical for soil profiles of a red-brown earth (Alfisol) and a black earth (Vertisol) were used with each climatic data set. The conditions described in these simulations should be similar to those of Alston (1980) (red-brown earth and Waite Institute weather data) and Strong and Cooper (1980) (black earth and Jondaryan weather data).

To facilitate comparison between the two soils, the depths of layers were made equivalent. For each of the soils and sites, simulations were run with no fertilizer added and then with 65 kg N/ha as ammonium nitrate applied at planting at depths of 3,10,20,30, 40,50,60,90,120, and 150 cm. Placement depth is simulated in the model by assuming uniform incorporation within the layer of placement. Thus the 3 cm placed fertilizer is uniformly incorporated to a depth of 5 cm and the 60 cm placed fertilizer is uniformly incorporated in a layer between 55 cm and 75 cm.

Yield, N uptake, biomass, and apparent recovery of fertilizer in each of the depth treatments were compared to the surface placed (top layer, i.e., 3 cm) treatment as below:

$$\% \text{ difference} = [(Y_{(d,j)} - Y_{(s,j)})/Y_{(s,j)}] * 100$$

where:

$Y_{(d,j)}$ = yield (or uptake, biomass, or recovery) from the deep-placed treatment in year J

$Y_{(s,j)}$ = yield (or uptake, biomass, or recovery) from the surface-placed treatment in year J

Apparent recovery of fertilizer was calculated as:

$$AR_{(d,j)} = [(NUP_{(d,j)} - NUP_{(u,j)})/\text{Rate}] * 100$$

where:

$NUP_{(d,j)}$ = N uptake from depth treatment d in year j

$NUP_{(u,j)}$ = N uptake from unfertilized control in year j

Rate = Rate of fertilizer applied (65 kg N/ha)

Statistical comparisons of the yield, N uptake, biomass, and apparent recovery from deep-placed treatment with the surface placed treatments were made with the Student's t test.

6.5.2 Results and Discussion

Within the 20-year period of simulation, there was a large range of outcomes to the various depth of placement strategies. In some cases large yield advantages resulted, while in others large yield reductions due to deep placement were noted. No statistically significant (Table 6.8) advantages of deep placement in yield, biomass, uptake, or apparent recovery were noted in any of the four location/soil type simulations. Significant reductions in each of these four parameters were obtained at the deeper placement depths (usually 90 cm or below at Jondaryan or 60 cm or below at Waite Institute). In all instances placement below 20 cm resulted in a reduction in mean yield and median yield. These reductions were small at the shallower depths but became substantial when the fertilizer was placed below 60 cm.

The range of outcomes was broadest on the Jondaryan Vertisol (Figure 6.8). In 1 year a 90% yield advantage over that obtained from surface placement was obtained by placing the fertilizer at 60 cm. On this soil fertilizer placement at the various depths to 60 cm was equally likely to result in yield advantages as yield disadvantages. Thus the data obtained by Strong and Cooper (1980) in the first year of their study fall within the range of simulated outcomes but differ substantially from the mean of all outcomes. The range of outcomes for the Alfisol at Jondaryan (Figure 6.9) was narrower than for the Vertisol. Since the amount of water retained

Table 6.8. Mean Percentage Variation From Surface Incorporation in Yield, Biomass, N Uptake and Apparent Recovery of Fertilizer for Various Depths of Placement

Jondaryan

	Alfisol				Vertisol			
Depth	Yield	Biomass	N Uptake	Recovery	Yield	Biomass	N Uptake	Recovery
10	-5.10	-2.33	-1.82	-4.18	1.66	4.81	3.57	5.44
20	-6.60	-3.97	-3.81	-9.00	-0.98	3.49	2.39	2.18
30	-6.46	-3.83	-3.77	-8.39	-3.04	-0.50	-1.42	-3.86
40	-6.49	-4.42	-5.25	-11.56	-4.97	-3.36	-5.05	-9.41
50	-6.89	-5.27	-6.23	-13.25	-0.59	-1.02	-3.00	-8.73
60	-5.09	-5.91	-6.18	-11.54	-0.30	-7.72	-5.52	-11.09
90	-12.26	-15.52*	-13.98*	-26.62*	-15.41	-21.59*	-18.42*	-20.58*
120	-33.90*	-33.93*	-29.67*	-60.92*	-32.21*	-34.97*	-32.78*	-51.32*
150	-48.17*	-45.40*	-42.07*	-88.37*	-42.37*	-42.04*	-41.85*	-43.05*

Waite Institute

	Alfisol				Vertisol			
Depth	Yield	Biomass	N Uptake	Recovery	Yield	Biomass	N Uptake	Recovery
10	0.39	0.62	0.30	0.53	0.23	0.52	0.09	0.31
20	0.27	-0.05	-0.39	-0.80	-0.51	-0.42	0.26	0.47
30	-0.06	-0.64	-0.77	-1.45	-0.59	-0.61	-0.34	-0.56
40	-2.00	-2.95	-2.66	-4.58	-5.13	-4.32	-7.23	-11.73
50	-4.59	-6.60	-5.83	-9.81	-10.99	-15.45*	-12.17*	-19.65*
60	-8.19	-13.25*	-12.36*	-20.61*	-28.63*	-39.38*	-35.40*	-56.69*
90	-20.57*	-30.61*	-29.42*	-49.05*	-34.67*	-47.32*	-42.99*	-69.16*
120	-36.81*	-46.49*	-44.98*	-75.16*	-47.23*	-56.84*	-54.17*	-87.43*
150	-49.93*	-56.37*	-55.40*	-92.75*	-53.18*	-60.87*	-60.12*	-92.27*

*Indicates a significant difference at the 5% level from the surface incorporation treatment.

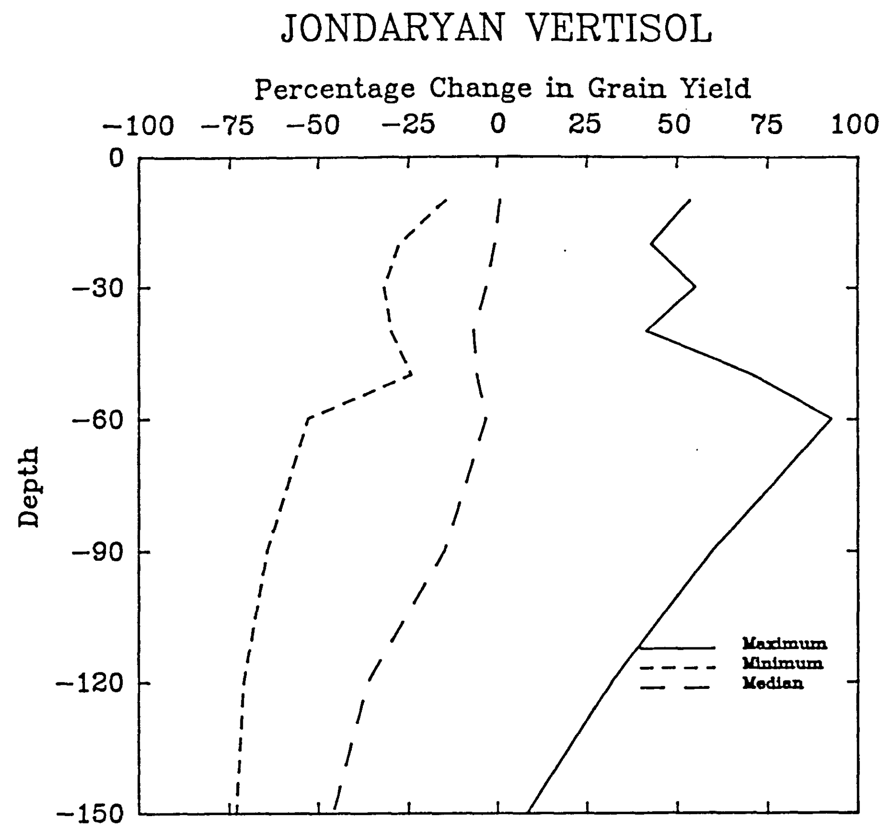

Figure 6.8. Range of Responses in Simulated Grain Yield to Depth of Placement of Fertilizer on a Vertisol at Jondaryan.

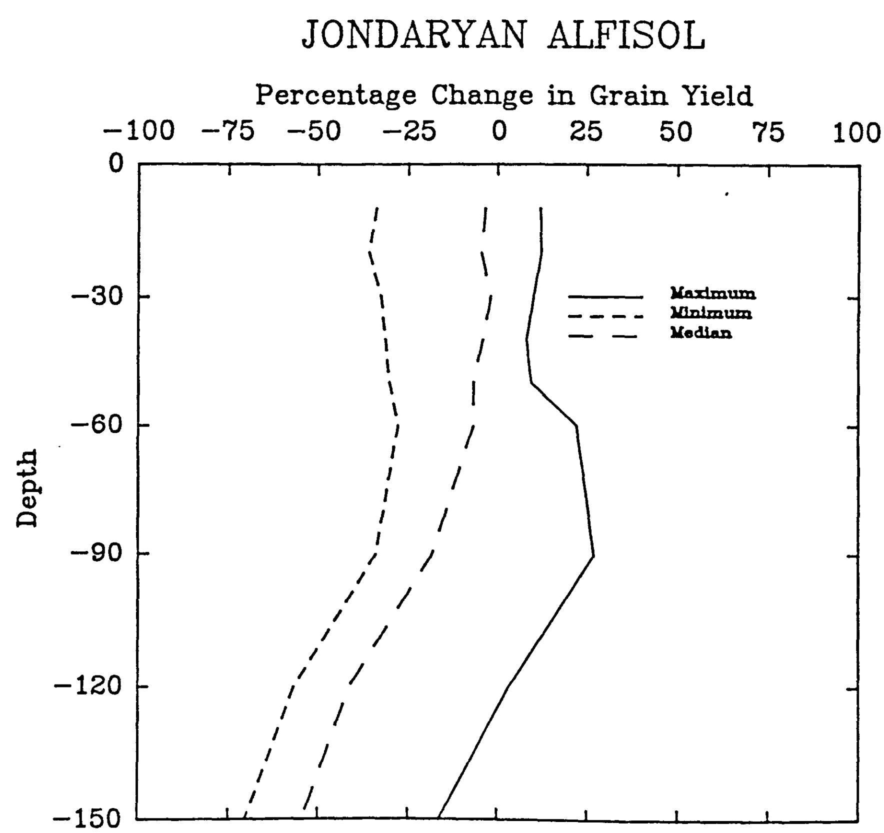

Figure 6.9. Range of Responses in Simulated Grain Yield to Depth of Placement of Fertilizer on an Alfisol at Jondaryan.

Table 5.15. Number of Months Where Generated Mean Monthly Rainfall Was Significantly Different From the Long-Term Observed Mean Monthly Rainfall

Period Used[a]	Esperance	Barraba	Bathurst	Biloela	Hamilton	Quirindi	Young
50 years	0	0	1	0	1	1	2
40 years	0	1	3	2	1	2	4
30 years	0	1	3	0	1	1	3
20 years	3	2	5	1	3	3	5
Decade 1	2	4	8	2	7	5	4
Decade 2	1	3	3	2	6	3	6
Decade 3	2	5	4	2	5	4	7
Decade 4	2	2	4	1	6	3	5
Decade 5	2	4	5	3	7	7	8
CV[b]	18	26	28	26	17	25	30

a. 50 years 1931-1980 for all sites except Hamilton (1921-1980) and Esperance (1911-1960); 40 years 1941-1980; 30 years 1951-1980; 20 years 1961-1970 or corresponding periods from Esperance and Hamilton. Decades refer to the first, second, third, fourth, or fifth decade of the sequence.
b. Coefficient of variation (%) of observed annual rainfall.

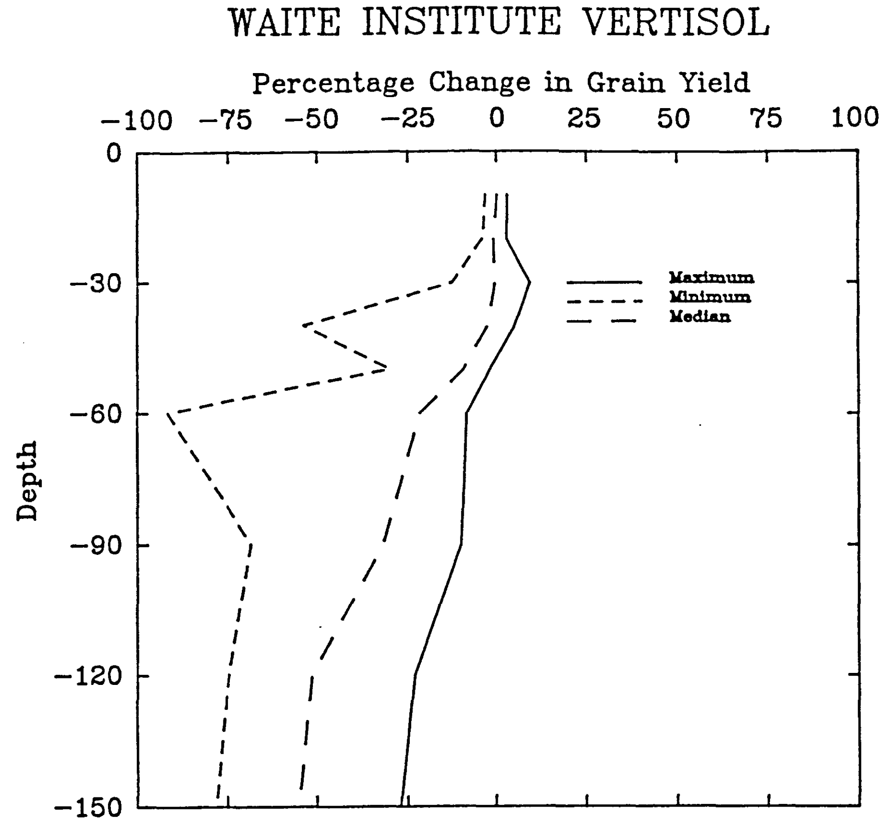

Figure 6.10. Range of Responses in Simulated Grain Yield to Depth of Placement of Fertilizer on a Vertisol at Waite Institute.

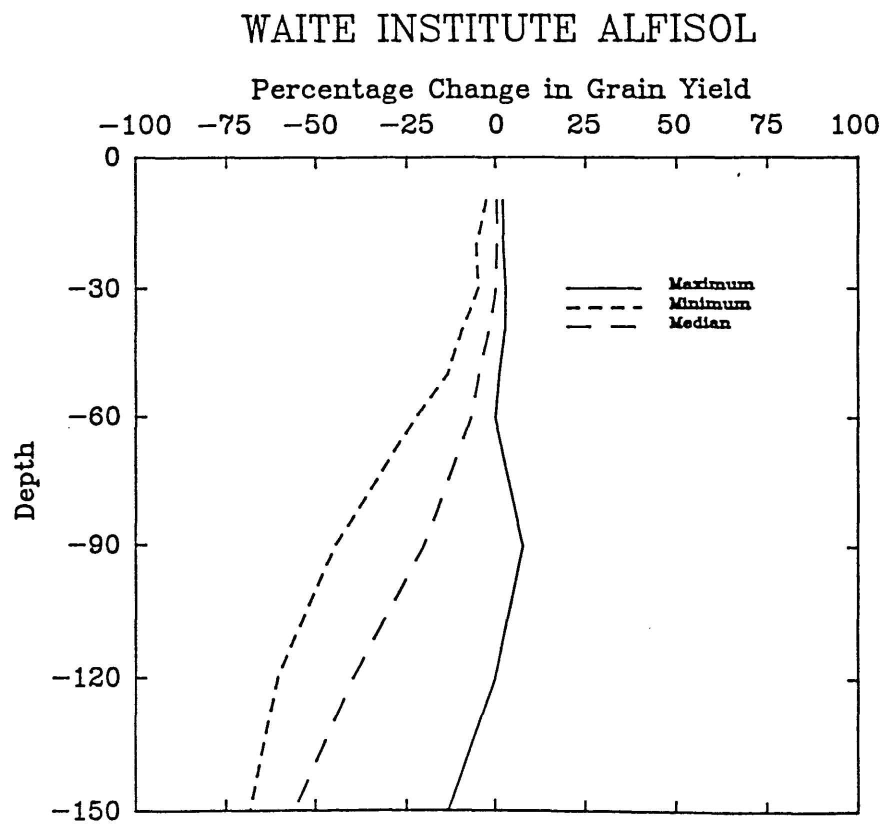

Figure 6.11. Range of Responses in Simulated Grain Yield to Depth of Placement of Fertilizer on an Alfisol at Waite Institute.

This study thus indicates that the model is sensitive to fertilizer placement depth when conditions are appropriate, and also serves to illustrate that single season fertilizer management studies need to be interpreted in the light of the magnitude of expected temporal variability.

6.6 Sensitivity to Nitrification Inhibition

Godwin and Vlek (1985) used the CERES-WHEAT-N model coupled to the WGEN weather generator (Richardson, 1981) to simulate N dynamics in wheat-cropping systems in three diverse locations. At Rothamsted (England) 50 years of daily generated weather data were used and genetic coefficients for a wheat variety representative of those typically grown in the region were used. The simulated crop duration using these coefficients was approximately 11 months. The soil type used in this study was a fine textured sand (Psamment).

At Rothamsted, nitrate leaching and denitrification were identified as the major causes of the simulated poor recovery of fertilizer. Annual denitrification losses from an application of 90 kg N/ha ranged from 0 to 35 kg N/ha with a median value of 17 kg N/ha/yr. In 50% of the years, 45 kg N/ha was leached from a layer 50 cm deep in the profile. The disposition from this layer may not necessarily be a loss to the crop, but its movement to deeper layers may affect subsequent uptake patterns and the distribution of root growth. Over the 50-year period of simulation the range of nitrate movement through the layer was from 20 kg N/ha/yr to 100 kg N/ha/yr. Losses of up to 70 kg N/ha/yr with a medium rate of 37 kg N/ha/yr as nitrate from a layer 1 m deep were simulated.

Denitrification and leaching are thus major avenues of loss of nitrate from soils. Various compounds can be added to an ammoniacal fertilizer to either kill nitrifying organisms or interfere with their metabolism such that nitrification is effectively blocked. The role and use of nitrification inhibitors have been the subject of several reviews (Meisenger et al., 1980; Hoeft, 1984).

To examine the impact a nitrification inhibitor may have, a simulation study using the simulated soil and climatic data for Rothamsted cited above was conducted. In this study 100 kg N/ha as an ammoniacal fertilizer was applied at planting. One 50-year run of the model allowed nitrification to proceed normally and another run had nitrification blocked for a period of 30 days following the application. The 30-day period of nitrification inhibition is within the range of longevities for commercially available inhibitors cited by Hoeft (1984). The output from the two simulation runs are expressed in terms of cumulative probabilities to illustrate the range and frequency of outcomes.

The simulated addition of an inhibitor resulted in a reduction in leaching from the 50-cm layer in all years (Figure 6.12a) but made little difference in 40% of the years from the layer 1 m deep (Figure 6.12b). Denitrification was reduced approximately 20% in all years (Figure 6.12c), but these reductions in losses resulted in only a small improvement in fertilizer apparent recovery (Figure 6.12d) with no consequences for improvement in grain yield (Figure 6.12e).

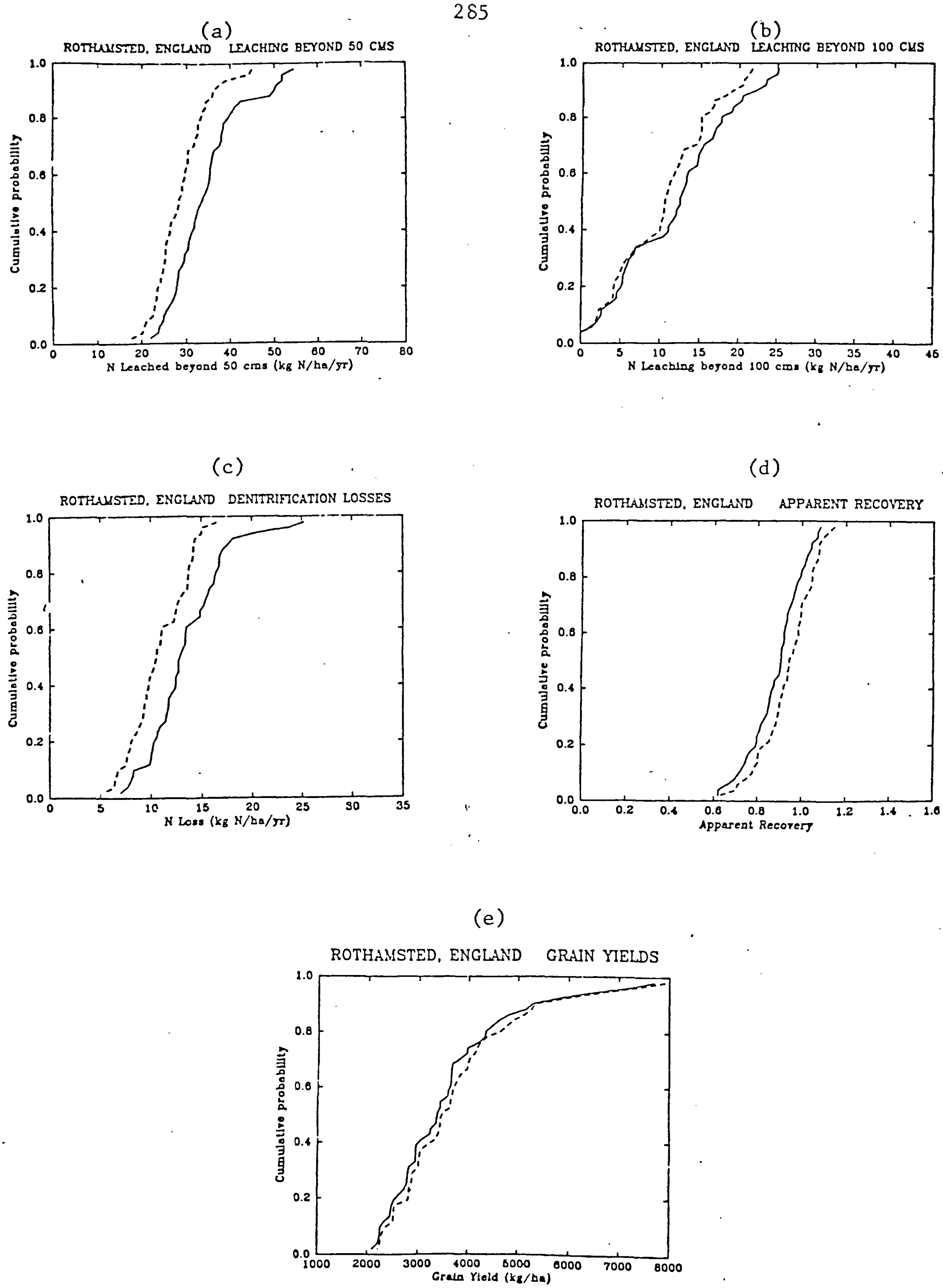

Figure 6.12. Rothamsted England Simulated Effect of Nitrification Inhibition.
Cumulative Probability Distributions of Simulated:

a. Rates of Nitrate Leaching From a Layer 50 cm Deep.
b. Rates of Nitrate Leaching From a Layer 1 m Deep.
c. Rates of Denitrification.
d. Apparent Recovery (%) of Fertilizer.
e. Grain Yield.

The Solid Line is for No Nitrification Inhibitor and the Dashed Line is for Nitrification Blocked for 30 Days.

6.7 Conclusions

The model is highly sensitive to the quality of the climatic data supplied to it as input. Soil physical and fertility inputs do also exert large influences on model outputs when circumstances are appropriate. The degree of accuracy provided by any simulations will thus be largely a reflection of the accuracy of these critical inputs. The impact and direction of errors resulting from errors in description of input data is greatly influenced by the prevailing climatic and edaphic factors described by the model. In many instances it will be impossible to determine *a priori* the magnitude of errors in simulated outputs associated with errors in model inputs.

The lack of sensitivity of many of the internal relationships within the model indicates that errors in the estimation of the rate of some processes are compensated for by feedbacks within the model, yielding little overall effect. Often this may lead to a situation of getting the "right answer for the wrong reasons," but does indicate a general overall robustness of the model in that simulations do not necessarily go awry when some functions are poorly estimated. This applies particularly to the subcomponents of the plant growth portion of the model.

The impact of perturbing the rate coefficients for the various nitrogen transformations is highly dependent on the nitrogen fertility status and also on temporal variability. For example, increases in denitrification rate may have little effect when adequate N for crop growth remains and in years when it is too dry for it to occur anyway.

Realistic simulation of various experiments with differing patterns of fertilizer management, fertilizer sources, or depths of placement indicated that the model does have great sensitivity to fertilizer management and provides further evidence of the model's validity. The ability to capture these management effects and to accommodate temporal variability illustrates the versatility of the model as a valuable adjunct to fertilizer research.

Table of Contents

7.1. Introduction to Risk Analysis

Losses of N, fertilizer recovery, grain yield, and the processes affecting these vary greatly from year to year in any location. Thus, to develop optimal fertilization strategies in any location it would be desirable to have fertilizer experiments conducted over many years. Fertilizer experiments are rarely conducted for more than two seasons and thus long-term data providing insights into the nature of temporal variability are usually not available. Simulation models running with either long-term weather data or with a weather simulator as outlined in Chapter 5 can readily produce a sequence of fertilizer response data over time.

When such data have been assembled the problem of interpretation exists. Means can readily be calculated from the temporal data but good decisionmaking will require more information than simply a knowledge of the average or most likely response (Dent and Blackie, 1979). It is desirable to know the risk associated with a particular strategy as well as the mean outcome. Agricultural economists have devoted much time and effort developing procedures for selecting strategies under conditions of uncertainty and providing due recognition to farmers' attitudes to risk. These procedures, known as risk analysis, have only rarely been adopted by agronomists and soil scientists. Anderson (1974a) has pointed out that modellers have a responsibility to provide decisionmakers with guidance and data which recognize the full extent of risk inherent in any strategy.

The first requirement for strategy evaluation is to have a model which will reliably perform under the conditions to be considered and to adequately specify all the stochastic elements. Dent and Blackie (1979) provide details on stochastic specification.

The procedures involved for selection of strategies under uncertainty have been described by Hadar and Russell (1969) and have been the subject of excellent reviews by Anderson (1974b) and Anderson et al. (1977). To provide some background to the analyses that follow a brief overview of the techniques follows. The techniques rely heavily on Bernouillian utility concepts, but a review of Bernouillian Utility Theory as it pertains to this subject is beyond the scope of this thesis.

7.2. Strategy Selection Under Uncertainty

Figure 7.1 illustrates the hypothetical case of a grain yield response to fertilizer in three contrasting years. In a favorable year (A) the response is linear over the range of rates applied and in an extremely unfavorable year (C) the response is small but quadratic with the very high rates of fertilizer leading to a lower yield than when no fertilizer was applied. The response in other years (B) may have a different form. The problem of defining an optimal rate of fertilizer given this year to year variability is obvious.

The response to fertilizer can be simulated over a 50-year period (Figure 7.2) and the variability in response is clearly apparent. By ranking the yields associated with each of the fertilizer rates into ascending order and assigning a 2% probability (1 year in 50) to each yield a cumulative probability density function (CDF) (Figure 7.3) can be formulated. This is not a true CDF but a linear segmented estimation of the CDF. The plotted CDF's convey a wealth of information vis: (1) The range of response from any individual treatment can

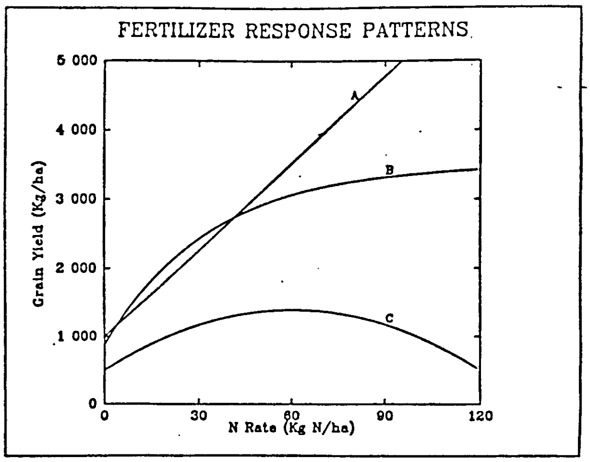

Figure 7.1. Hypothetical Yield Responses to Applied Fertilizer.

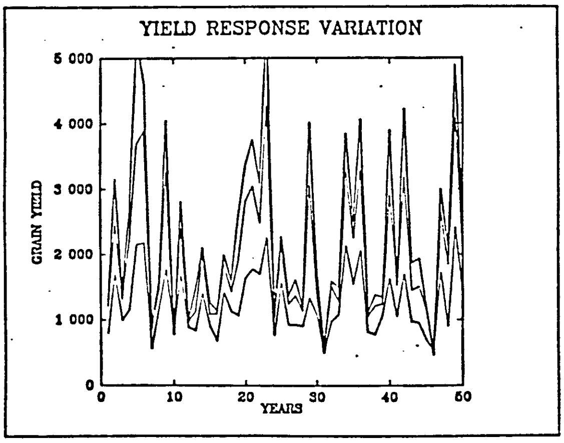

Figure 7.2. Variation in Simulated Yield and Response to Fertilizer Over a 50-Year Period at Dubbo. Lower Line 0 kg N/ha, Upper Line 60 kg N/ha, Intermediate Line 30 kg N/ha.

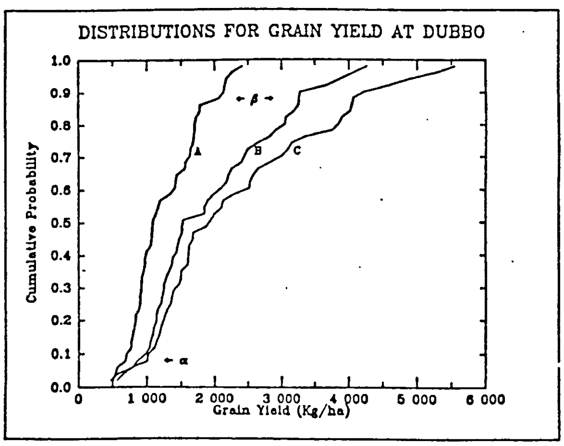

Figure 7.3. Cumulative Probability Density Function for Simulated Grain Yield Response to Three Fertilizer Strategies at Dubbo. (A = 0 kg N/ha, B = 30 kg N/ha, C = 60 kg N/ha).

readily be gleaned (e.g., from 500 to 2,500 kg/ha for strategy [A]). (2) The frequency with which yields associated with strategy B are superior to those associated with strategy A is readily discernable. (3) If strategies A, B, and C are equally spaced rates of fertilizer (e.g., 0, 30, and 60 kg N/ha) some insights into the nature of the response patterns can be gleaned. In low-yielding years (α in Figure 7.3) little response is apparent since the CDF's for the rates lie close to each other. In high-yielding years (β in Figure 7.3) the CDF's are widely separated, indicating a large response. Thus, in this location large responses to fertilizer are most apparent in the highest yielding years (the most typical case). The frequency with which the response is apparent is also readily attainable from the plot. (4) The best strategy is easily discernable from the figure as the one most displaced to right (C). This strategy has a higher frequency of more favourable outcomes than the others. It may be termed the most stochastically efficient strategy.

Problems in interpretation can occur when the CDF's cross and the procedures to separate them to identify the most efficient strategy require some further elaboration.

When the CDF for a strategy is displaced to the right of another strategy over the whole of its range, then this is known as first degree stochastic dominance (FSD). This is the preferred strategy and is based on the premise that if x is an unscaled measure of consequence such as yield or profit, decisionmakers will always prefer to have more to less of x. Anderson et al. (1977) have formalized this as the assumption of a monotonically increasing utility function wherein the first derivative is strictly positive (i.e., $U\ (x) > 0$). They define FSD as:

> Consider the case of a pair of continuous CDF's F_1 and G_1 defined within the range (a,b) and respectively associated with two acts or risky prospects F and G. F_1 is related to its PDF f (x) by
>
> $$F_1(R) = \int_a^R f(x)dx$$
>
> F is said to dominate G in the sense of first-degree stochastic dominance (FSD) if $F_1(R) \leqq G_1(R)$ for all possible R in the range (a,b) with at least one strong inequality (i.e., the < holds for at least one value of R).

FSD is illustrated in Figure 7.4.

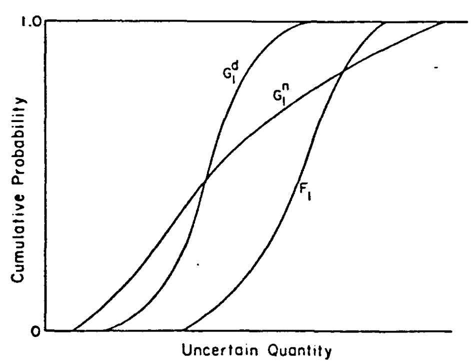

Figure 7.4. Illustration of First Degree Stochastic Dominance (FSD). F_1 Dominates $G_1{}^d$ but not $G_1{}^n$). (From Anderson et al., 1977).

Often the CDF's intersect at least once which means the strategies cannot be separated on the basis of FSD. In these cases the rules applying to second-degree stochastic dominance (SSD) can be applied to help separate strategies. With SSD the utility function over the range (a,b) is not only monotonically increasing but is also strictly concave with the second derivative positive (Anderson et al., 1977). A case of SSD is illustrated in Figure 7.5. To separate the strategies using SSD a further type of cumulative function that measures the area under a CDF over the range (a,b) is required. Anderson et al. specify this as:

Define the SSD cumulative for a distribution F_1 as

$$F_2(R) = \int_a^R F_1(x)dx$$

Then the distribution F is said to dominate G in the sense of SSD if $F_2(R) \leqq G_2(R)$ for all possible R with at least one strong inequality.

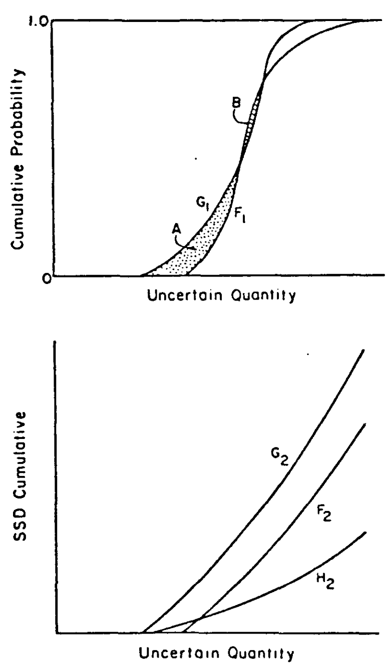

Figure 7.5. Illustration of Second Degree Stochastic Dominance (SSD) Where CDF's Cross Twice (Area A > Area B). (From Anderson et al., 1977).

A typical case where the CDF's cross requiring SSD to separate strategies could occur in marginal wheat-growing areas where F_1 represented a low rate of fertilizer and G_1 a higher rate of fertilizer. In low-yielding years (presumably dry years) increasing rates of fertilizer led to reductions in yield (cases of this are further discussed in Chapters 4 and 6). In wetter years there may be sufficient moisture to enable the crop to respond to fertilizer. These are the highest yielding years.

By extending the analysis further, risk efficient strategies may be identified by third degree stochastic dominance (TSD). In this case the third derivative of the utility function is positive. Anderson et al. define TSD as:

> The TSD ordering rule requires the definition of a further type of cumulative function, namely the area under the SSD cumulative function:
>
> $$F_3(R) = \int_a^R F_2(x)dx$$
>
> The distribution F dominates G in the sense of TSD if $F_3(R) \leqq G_3(R)$ for all possible R with at least one strong inequality and if $F_2(b) \leqq G_2(b)$, where b is the upper range, or equivalently, $E_F(x) \leqq E_G(x)$.

By further extension of the procedure strategies may also be separated by fourth degree stochastic dominance but this warrants no further discussion.

7.3. Description of the Simulation Study

7.3.1. Introduction

As illustrated in Chapter 5, the Australian wheat belt is characterized by a diversity of climates and a notoriously unreliable rainfall.

Areas in the northerly latitudes of the eastern Australian wheat belt have a summer dominant rainfall and a relatively short growing season due to the prevailing temperatures. Southern areas of the wheat belt have a Mediterranean-type climate with a winter rainfall and a summer drought. Coincident with this diversity of climates is a diversity of soil types utilized for growing wheat and a diversity of crop genotypes.

The sensitivity of the model to changes in climate, soil type, and genotype has been previously demonstrated, as has its ability to simulate nitrogen dynamics and crop growth reliably. The objectives of this study were to determine whether differences in response to various fertilizer strategies are detectable in the various environments and whether the modelling approach is a viable procedure for evaluating fertilizer strategies.

7.3.2. Simulation Methods

Five locations representative of different areas within the eastern Australian wheat belt were selected for the simulation study. These were:

Pittsworth-Old--Northern portion of wheat belt. Summer dominant rainfall.

Rutherglen-Vic--Southeastern portion of wheat belt. Winter dominant rainfall and sufficient rainfall for an N response.

Orange-NSW--Central portion of wheat belt. No marked summer or winter dominance of rainfall (high rainfall).

Dubbo-NSW--Central portion of wheat belt. Intermediate rainfall.

Trangie-NSW--Central portion of wheat belt. Low rainfall.

These locations are indicated on the location map (Figure 5.4). Pittsworth, Orange, and Rutherglen thus form a north-south transect--the wetter (and presently more fertilizer responsive) eastern edge of the wheat belt. Orange, Dubbo, and Trangie form an east-west transect in the central portion of the wheat belt and the locations differ markedly in annual and growing season rainfall. Differences in the thermal environment occur at the five sites and this affects the growth duration. For each of the locations, the weather generator coefficients described in Chapter 5 were used to generate a 50-year sequence of daily weather data.

A red-brown earth (Rhodustalf) 150-cm deep and capable of holding 32 mm of plant-extractable water was chosen as a representative soil to use in the simulations. The whole profile drainage rate coefficient (SWCON, see Chapter 3) for this soil was 0.4. This soil had 62 kg N/ha of initial extractable mineral N in the profile immediately prior to planting. It is acknowledged that many other soils exist within the wheat belt (e.g., vertisols in the northern regions) but the interest in this study is to examine purely the risk associated with climatic uncertainty. A later study not reported here also examined the effect of various soil types on fertilizer response.

An assumed planting date of May 29 (150th day of the year) was used in each simulation and genetic coefficients appropriate for the cultivar Condor were used as model inputs. This planting date and cultivar selection represented a compromise between possible earlier planting dates at some sites and both later and earlier planting dates in the northern locations. This cultivar was one of the most widely planted in the late 1970s and early 1980s in the region. The predicted germination date was dependent on simulated moisture in the planting layer and temperature.

At each site 11 fertilizer strategies were examined. These consisted of five strategies where fertilizer was all applied at planting and six strategies where fertilizer application was delayed until some time after planting or where half of the fertilizer was applied at planting and the remainder some time after planting. Fertilizer strategy code numbers, rates, and times of application are indicated in Table 7.1. The intermediate rate of 60 kg N/ha was chosen for comparison of strategies involving either delayed or split applications. For each fertilizer strategy studied 50 crops were simulated.

Table 7.1. Fertilizer Application Patterns Used in the Simulation Study (Numbers indicate amount of N applied in kg N/ha)

Strategy Code	Total Rate	At Planting	Days After Planting 50	70	110
1	0	0	-	-	-
2	30	30	-	-	-
3	60	60	-	-	-
4	90	90	-	-	-
5	120	120	-	-	-
6	60	30	30	-	-
7	60	30	-	30	-
8	60	30	-	-	30
9	60	0	60	-	-
10	60	0	-	60	-

In each of the 50 crop years the initial soil nitrogen availability but not soil-water availability, was initialized to the same value 10 days prior to planting. The amount of extractable soil-water present at this time was that determined by simulating a fallow period immediately prior to this time. The rationale behind this is to examine the variability in 50 crops each of which start with all conditions the same, except those caused by climate. It should also be clarified that the simulations are not of sequential crops but of 50 independent crops. The procedure used in each analysis assumes the observations used to formulate the CDF's are independent events and this can have no serial dependence as sequential crops would have.

For each strategy studied, a CDF for grain yield was estimated using 50 linear segments defined by the 50 years of simulation. To estimate these CDF's, the simulated yields for a particular treatment were sorted into ascending order and each year assigned a probability of 2%. Probability deciles were then interpolated from the CDF's and means calculated.

In some instances most efficient strategies were identified by using a modified version of the SDOM procedure described by Anderson et al. (1977). The procedure is based on the principles reported in 7.2 above. Fertilizer strategies involving either a split or a delayed application were compared to a reference simulation where all the fertilizer was applied at planting. Comparisons are reported as a yield advantage (positive or negative) over the reference simulation based on the following calculation.

Yield advantage (n,j) = Yield (n,j) - reference yield (j)

where,

j = year 1 to 50.

n = strategy number.

By changing the amount and timing of the supply of nitrogen to the crop, different fertilizer practices may cause differences in the timing of the onset of water and nitrogen stress within the crop. To examine this possibility stress indices for water and nitrogen for each crop growth stage were calculated. A water stress index based upon the ratio of potential transpiration to root water was calculated. This stress index is expressed on a zero to unity basis and is the same as the index used to modify the rates of leaf expansion growth (SWDF2). To determine how much stress occurred during a growth stage, this index was accumulated and then divided by the number of days of duration of the stage. When the resulting index has a value of unity, it means that growth was limited by water stress to the maximum extent on every day during the growth stage. When this index has a zero value, no water stress occurred during the growth stage. A similar stress index for nitrogen was also calculated. CDF's for these stress indices were constructed for each fertilizer strategy. CDF's for apparent recovery of fertilizer, denitrification losses, and nitrate leaching losses were also calculated for each strategy.

7.4. Results and Interpretation

The patterns of response to N differed at each site (Figure 7.6). There was a much greater range of responses at Orange than at the other sites. Higher yields at Orange were associated both with a simulated higher amount of rainfall during the growing season and a longer duration growing season (Table 7.2). The variability of crop yields as expressed by the coefficient of variation increased with decreasing mean annual growing season rainfall.

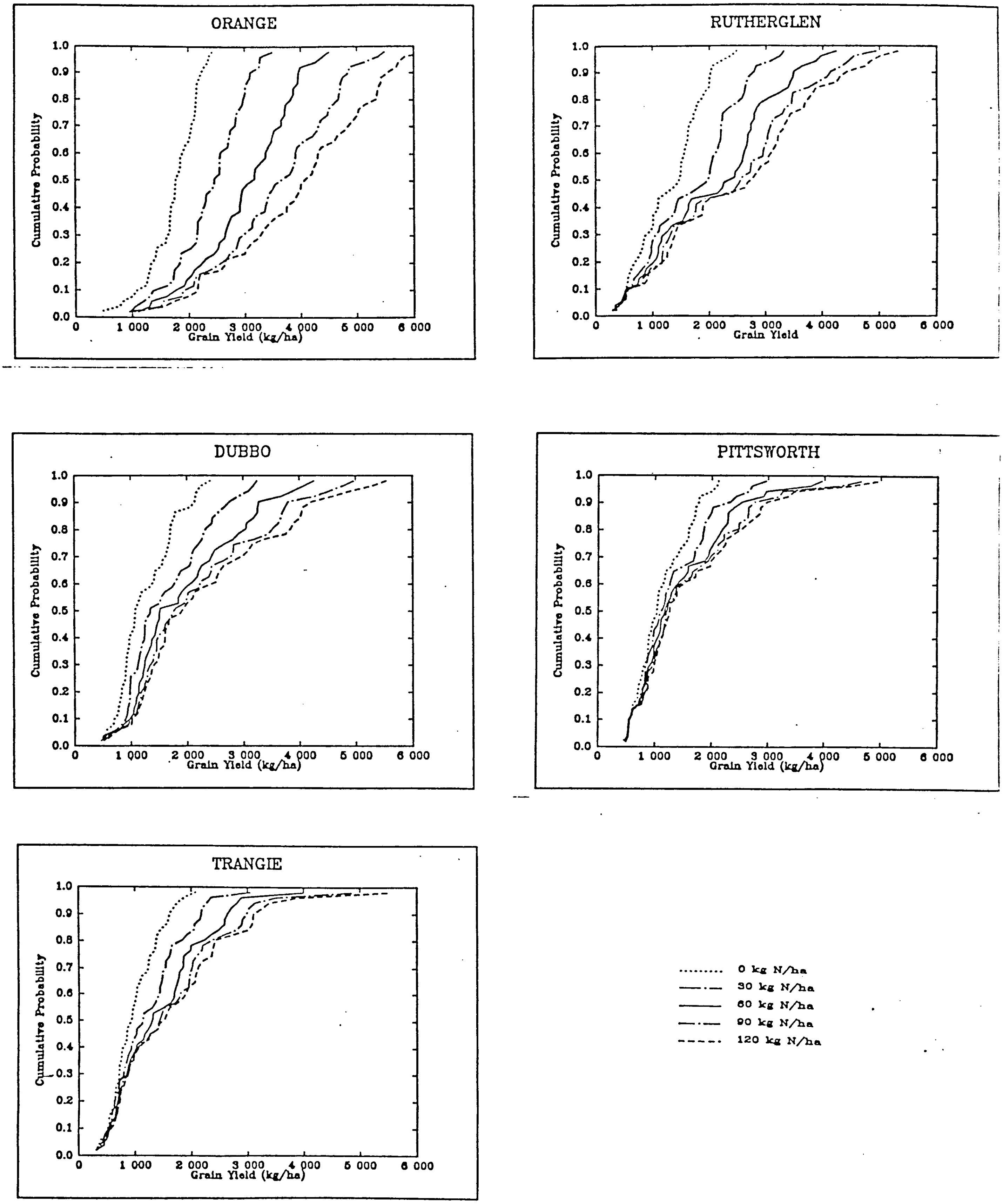

Figure 7.6. Cumulative Probability Density Function for Simulated Grain Yield Response to Five Rates of N Fertilizer at Five Locations.
(a) Orange
(b) Rutherglen
(c) Dubbo
(d) Pittsworth
(e) Trangie

Table 7.2. Simulated Rainfall and Yield Ranges at Five Sites in the Simulation Study

	Orange	Dubbo	Trangie	Pittsworth	Rutherglen
Latitude (°s)	33.17	32.15	32.02	27.43	36.03
Mean annual rainfall (mm)	867	581	496	698	592
Simulated growing season length[a]	202	169	168	155	188
Simulated median rain during the growing season (mm)	471	240	207	202	277
Simulated mean yield at 120 kg N/ha	3,938	2,337	1,682	1,630	2,521
Coefficient of variation for yields at 120 kg N/ha (%)	32.7	55.5	64.0	62.5	54.3
Simulated maximum yield (kg/ha) in 50 years (120 kg N/ha)	6,281	5,540	5,475	4,933	5,316
Simulated minimum yield (kg/ha) in 50 years (0 kg N/ha)	437	502	312	438	285

a. Mean length in days from planting to harvest.

The CDF's for each fertilizer rate (see Figure 7.6a) are widely separated over most of their range, indicating that a large response to fertilizer occurs most of the time at this site. The CDF's are most widely separated at the top of the figure indicating that the largest responses to fertilizer occur in the highest yielding years. In approximately 25% of years no response beyond 90 kg N/ha occurs (CDF's for 90 kg N/ha and 120 kg N/ha rate lie very close together). Without considering economic factors the preferred strategy at Orange would be the 120 kg N/ha strategy. This strategy in terms of stochastic dominance is dominant to all others. As fertilizer rate was increased, the variability in yield increased. When no fertilizer was applied the yield range was from 502 kg/ha to 2,410 kg/ha, and when 120 kg N/ha was applied, the yield range was from 558 kg/ha to 5,540 kg/ha. The preferred strategy may be different if the outcomes were expressed in terms of profits rather than yields. An examination of fertilizer response measured in economic terms is beyond the scope of this thesis.

On the lower rainfall sites, the frequency of there being a response beyond 90 kg N/ha was very much diminished. At Dubbo CDF's for the 90 and 120 kg N/ha rates are indistinguishable in approximately 50% of years, and in the high yielding years, yields from these two strategies are not very different (Figure 7.6c). At Trangie, CDF's from all fertilizer rates are superimposed on the CDF for the zero rate in the less than 30% cumulative probability range. This means that in 30% of years there is no response to fertilizer and again this occurs in the low-yielding years. In the remaining years there is a clear response to 30 kg N/ha but response beyond 60 kg N/ha is unclear. At Pittsworth no clear response pattern is evident in at least 65% of years. At Rutherglen, responses are frequent and large compared to the drier sites.

Examination of the simulated N balance for the five sites indicated that N losses via denitrification and leaching were both infrequent and small, particularly at the drier sites. At all sites except Orange, leaching of nitrate beyond 50 cm occurred in less than 10% of years. At these sites the total amount leached in these years was less than 10 kg N/ha. At Orange the total amount leached depended on the rate of application. Some leaching occurred in at least 80% of years (Figure 7.7). The amount leached in these years varied from less than 1 kg N/ha to 18 kg N/ha. At no site did denitrification losses exceed 15 kg N/ha. Denitrification losses at all sites were less than 8 kg N/ha in 90% of years. Apparent recovery of fertilizer varied greatly from year to year (Figure 7.8). When comparing the three sites in the east-west transect, recovery was higher at Orange than the other sites in most years. At the drier sites poor recovery was associated with inability to take up N when it was too dry rather than due to losses. This is evident from an analysis of the frequency of moisture stress at Orange, Dubbo, and Trangie.

During grain filling (Stage 5) some water stress always occurred at Dubbo and Trangie (Figure 7.9). At Orange no water stress occurred during grain filling in about 30% of the years. The severity of water stress at Orange during grain filling was always less than at the other two sites. During Stage 3 (booting to ear emergence) water stress limits growth (and N uptake) in only 30% of years at Orange (Figure 7.10) but limits growth at Dubbo and Trangie in every year.

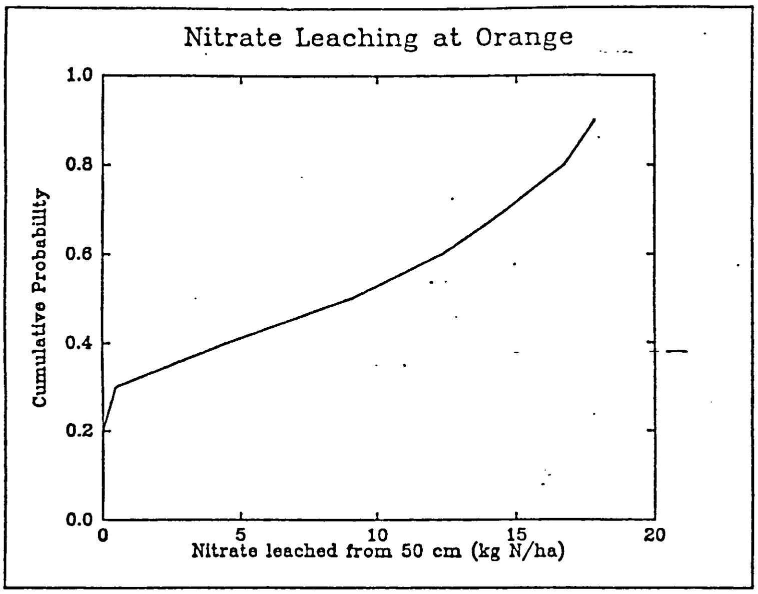

Figure 7.7. CDF for Nitrate Leaching From a Layer 50 cm Deep When 60 kg N/ha was Applied at Planting at Orange

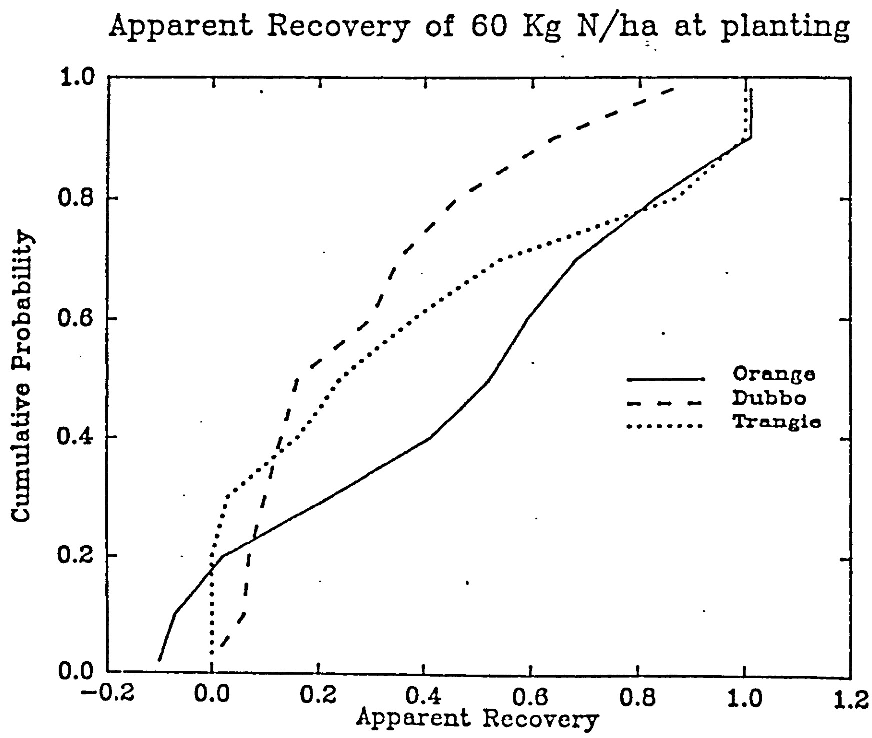

Figure 7.8. CDF's for Apparent Recovery of Fertilizer at Orange, Dubbo, and Trangie When 60 kg N/ha was Applied at Planting.

At Orange, growth is more often limited by N stress (Figure 7.11) than by water stress. Analysis of the stress indices for the other growth stages also indicates that growth is more frequently limited by water than by N supply at this rate of fertilizer application at Dubbo and Trangie. When little or no fertilizer is applied N stress becomes more frequent. When higher rates of nitrogen are applied at Orange the frequency and severity of water stress increases (Figure 7.12). Water and nitrogen stress patterns at Rutherglen were intermediate between those for Dubbo and Orange. Water and nitrogen stress patterns at Pittsworth were similar to those for Trangie.

Given that some N losses occur at Orange and that water does not often limit growth early in the season, some response to split applications of fertilizer might be expected. Figure 7.13 indicates that at Orange, fertilizer strategies which involve either delaying some or all of the application until later in the season frequently provided a yield advantage over the strategy of applying all the fertilizer at planting. In the case of strategies 6 and 10 yields were greater than with strategy 3 in about 75% of years but there were some years (about 20%) in which yields produced with strategy 10 were very much lower than those produced by strategy 3. Strategies 8 and 9 resulted in yield distributions similar to those from strategy 7. At Rutherglen (Figure 7.14) and Dubbo (Figure 7.15), splitting or delaying the fertilizer application frequently resulted in lower yields than applying all of the fertilizer at planting. In some years (from 10% to 50%) at Dubbo some yield advantage was attained by splitting or

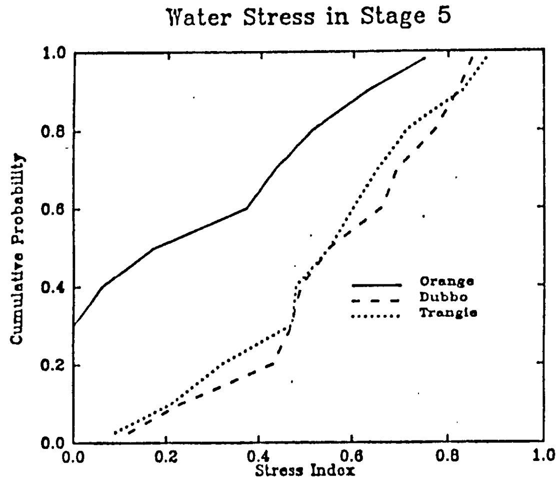

Figure 7.9. CDF's for Water Stress Occurring in Stage 5 at Orange, Dubbo, and Trangie When 60 kg N/ha was Applied at Planting.

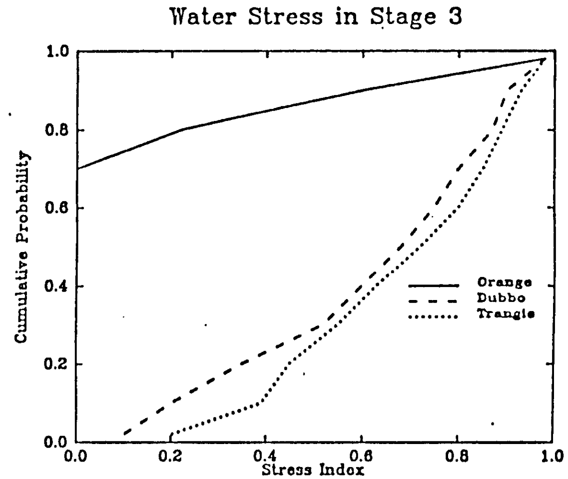

Figure 7.10. CDF's for Water Stress Occurring in Stage 3 at Orange, Dubbo, and Trangie When 60 kg N/ha was Applied at Planting.

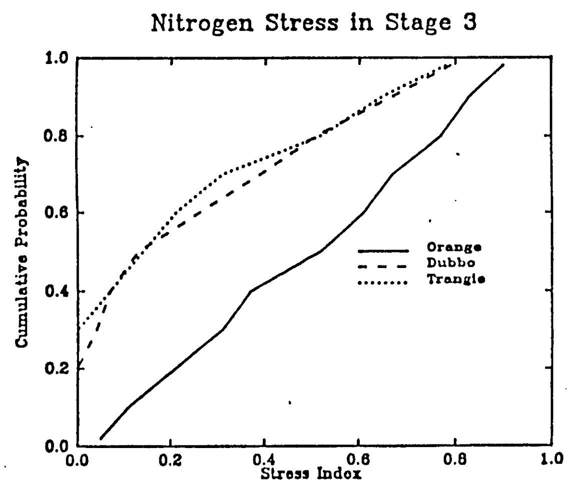

Figure 7.11. CDF's for Nitrogen Stress Occurring in Stage 3 at Orange, Dubbo, and Trangie When 60 kg N/ha was Applied at Planting.

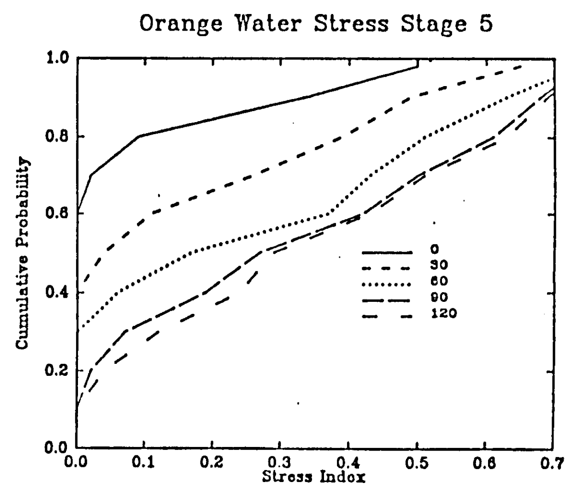

Figure 7.12. CDF's for Water Stress Occurring in Stage 5 at Orange, When Various Rates of Fertilizer are Applied.

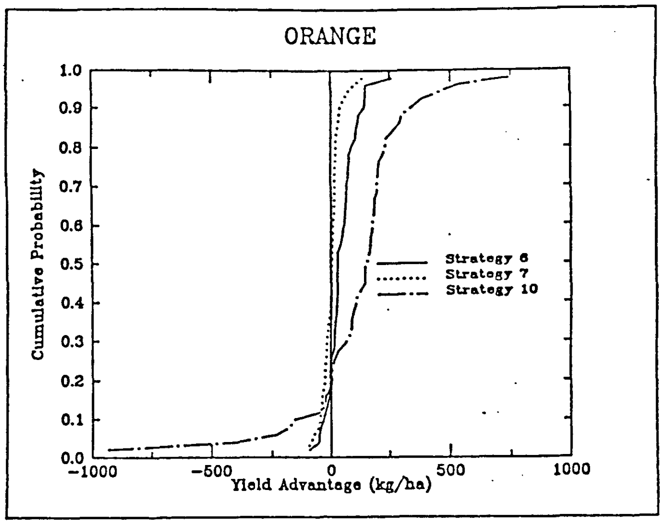

Figure 7.13. CDF's for Yield Advantages to Split or Delayed Applications of Fertilizer at Orange. The Comparisons are to Strategy 3 Which is Indicated by the Vertical Line at Zero Difference.

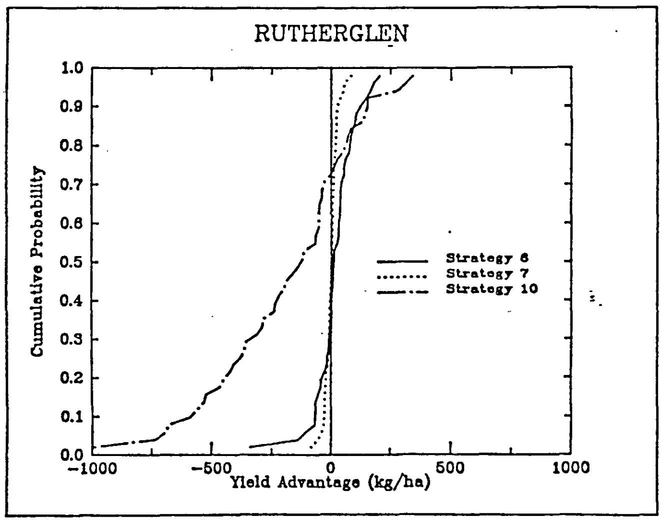

Figure 7.14. CDF's for Yield Advantages to Split or Delayed Applications of Fertilizer at Rutherglen. The Comparisons are to Strategy 3 Which is Indicated by the Vertical Line at Zero Difference.

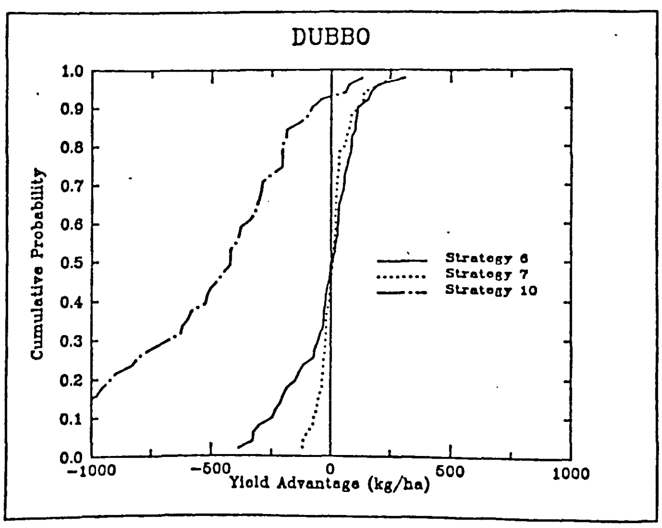

Figure 7.15. CDF's for Yield Advantages to Split or Delayed Applications of Fertilizer at Dubbo. The Comparisons are to Strategy 3 Which is Indicated by the Vertical Line at Zero Difference.

delaying the fertilizer application. At Rutherglen small advantages occurred in 30% to 50% of years. At Dubbo and Rutherglen the largest yield advantage occurred with strategies involving an early application of the second dressing, whereas at Orange yield advantages were attained by using a late split. In each location, strategy 10 involved the most risk (greatest variance of yields).

Given that strategy 3 and strategies 6 to 10 all use the same amount of fertilizer and therefore should have the same costs, it is appropriate to try to determine a preferred strategy. For the three locations where some response to splitting could be seen (Orange, Dubbo, and Rutherglen), the rules governing strategy selection under FSD cannot be used since the CDF's cross. When using the procedures for SSD and TSD the CDF's were still found to intersect and thus no one strategy could be identified as being uniquely preferred. Expressing the SSD in terms of a yield advantage or disadvantage over strategy 3 for Orange (Figure 7.16) indicates that strategies 6 and 7 are distinct from strategy 3 over most of their range.

7.5. Conclusions

Simulated losses of N from most of the wheat cropping systems studied were small. Significant losses only occur as leaching from very sandy soils or rarely as denitrification losses on the red-brown earth. It is conceivable that if a soil profile typical of a vertisol with poor drainage characteristics (lower SWCON) and with large amounts of organic matter present (particularly FOM), were used in the simulation then significant losses through denitrification may have been more frequently simulated. Ammonia volatilization which is not described by the model offers

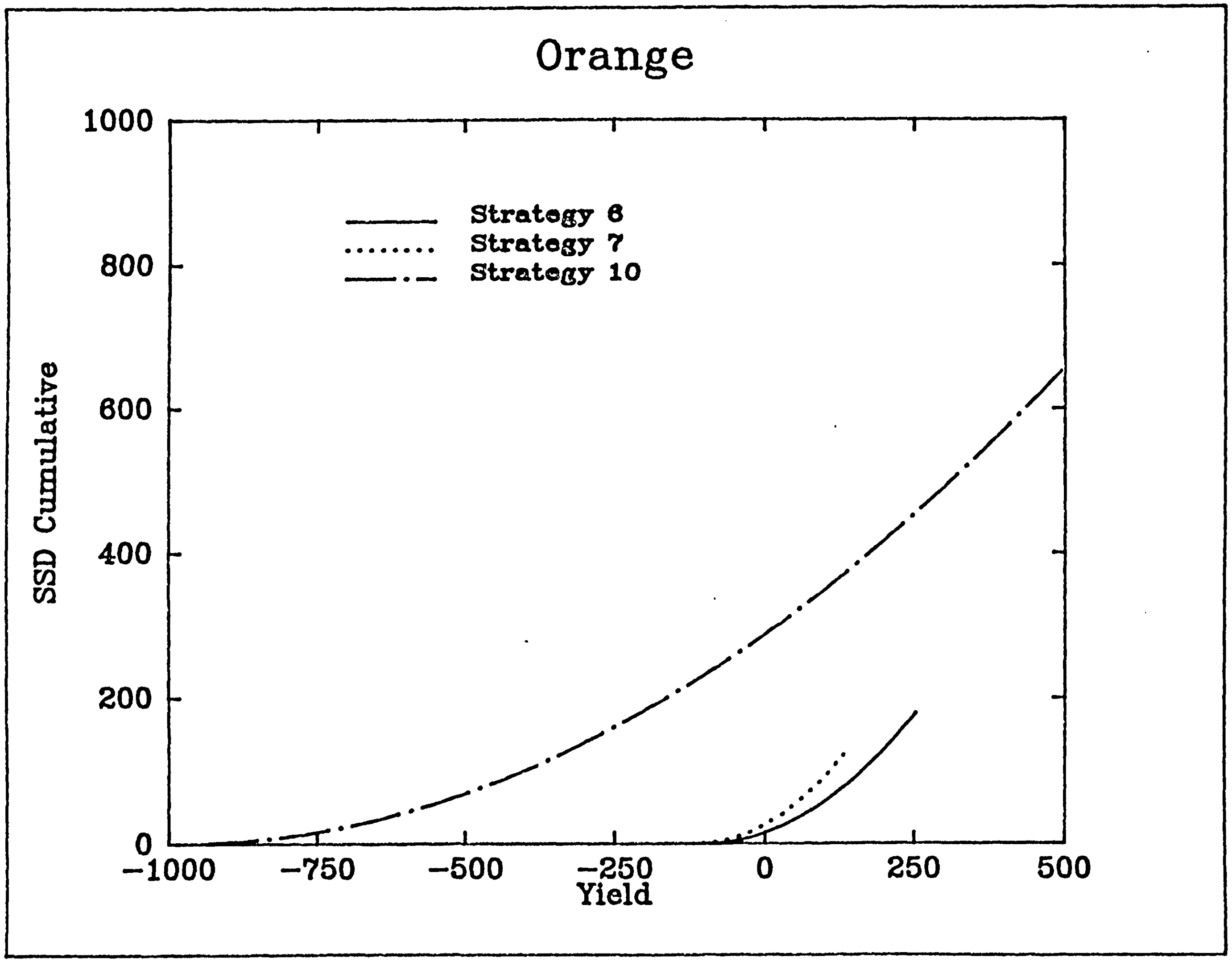

Figure 7.16. SSD Functions for Three Fertilizer Strategies at Orange.

a further avenue for nitrogen loss, but when fertilizer is incorporated in the generally low pH to neutral soils of the wheat belt, losses would not be expected to be large.

Given that N losses are generally small in the Australian wheat cropping environment, response to N is predominantly determined by the availability of water. The simulations demonstrated the capability of the model in describing the magnitude of the seasonal variations in growing season rainfall, and availability of soil water throughout the growing season and the resultant variations in response to fertilizer. The generally small losses of N and the variability in soil moisture throughout the season provide little scope for improvement of fertilizer management practices other than those currently practiced.

One possibility, however, may be to delay fertilizer applications until sometime after planting and then make a decision on a subsequent application and rate based on crop growth to date, soil and crop nutrient status and the amount of moisture in the soil. The study indicated that application could be delayed sometime after planting without sacrificing yield. The length of this delay would be dependent on the amount of mineral N in the profile at planting time and conditions after planting. Keatinge et al. (1986) termed this an "event conditioned" strategy, and considered this to be the most valid way of approaching fertilizer decisionmaking in the high risk environment of Northwest Syria. By lowering application rates when crop performance has been poor or when crop outlook is poor, savings in fertilizer and improvements in fertilizer efficiency could be made. This late "strategic" application when made on the basis of prevailing conditions offers the potential of reducing fertilizer input costs and allowing a farmer to hedge on the seasonal outcome.

When trying to determine the appropriate time and rate of the second or delayed application, the following factors need to be considered:

1. The developmental age of the crop in relation to seasonal norms for development.
2. The biomass of the crop.
3. The nitrogen status of the crop.
4. The mineral nitrogen status of the soil.
5. The amount of extractable water in the soil profile.
6. Probable weather patterns for the remainder of the crop growth period.

All of these factors suggest that the decision as to when and how much fertilizer to apply is a complex one. Multiple simulation runs may enable the formulation of "best bet" strategies and possibly aid in the development of the decision rules used in a fertilizer expert system.

A similar exercise (Baanante et al., 1986) to the one described in this study but with the CERES-MAIZE N model in two locations in Benin, West Africa has been conducted. It indicated considerably more scope for fertilizer management when N losses are large. These two exercises attest to the model's versatility as a tool to facilitate fertilizer research and management.

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8.1. General Conclusions on the Utility of the Model

Testing of the CERES-Wheat-N model indicated that it can be used with confidence in a diversity of environments. The model was found to be sensitive to the soil, climatic, genetic, and management information supplied to it. It should be stressed, however, that the model can only account for variations in the factors defined in the model's description and thus assumes that other potentially important factors such as the effects of other nutrients, pests, and diseases are nonlimiting. There are also certain processes in the N cycle and fertilizer management effects, which under some circumstances can be important, which are not simulated by the model. These are the subject of discussion below. Given these conditions the model was able to reasonably account for the observed variation in yield, biomass production, N uptake, protein content, and N balance in the studies examined.

The model, particularly when coupled to long-term weather data or generated climatic data, is a valuable tool for providing insights into the behavior of many aspects of the cropping system. Running the model with long-term weather data enables a quantification of the temporal variability in yield and response to fertilizer. The frequency and nature of N losses and other causes of poor fertilizer efficiency can be identified and there relative significance evaluated. The simulation studies on Australian wheat cropping systems (Chapter 7) indicated that losses of N via denitrification or leaching were generally small, although some redistribution of nitrate within the profile may occur. Given that these losses were small, the strategies evaluated by the model indicated only small scope for improvement in fertilizer efficiency. The studies did indicate, however, that in certain circumstances the strategy of delaying most of the fertilizer application until later in the season lead only to a small sacrifice, if any, in yield. Under favourable economic circumstances this strategy may be advantageous. This strategy enables the farmer to defer capital outlay until later in the growing season and then to adjust the rate of application according to the current status of the crop and the likelihood of favourable outcomes.

Where N losses are more substantial the model has greater utility in defining appropriate strategies. A similar exercise to that outlined in Chapter 7 in the CERES-Maize-N model on the tropical soils in Benin, West Africa (Baanante et al., 1986) indicated large differences in strategy. The model thus is a valuable tool for evaluating fertilizer strategies and defining losses, enabling researchers to maximize efficiency under the circumstances of climatic variability. The CERES-MAIZE model has also been used in a study (Boggess, 1986) to assess the risk associated with irrigation in a humid area and the CERES-RICE model has been coupled (Alocilja and Ritchie, 1986) to tools for estimation at economically optimal inputs in rice cropping systems. The maize model has also been adopted to applications in irrigation and fertilization scheduling (Hodges, 1986). These varied applications of the CERES models, together with those described in this thesis, indicate that models are well suited to applications in agricultural management and policy analysis.

8.2. Areas for Further Study

8.2.1. Soil N and Fertilizer Components

There are several applications in the evaluation of fertilizer strategies where the model has some shortcomings. Paramount among these is the lack of procedures to simulate the volatile loss of ammonia from the soil. Several models now exist for simulation of this process, but unfortunately most require a large set of parameters or would not otherwise lend themselves to adoption to the CERES model.

Significant ammonia loss could be expected to occur when certain fertilizers are surface applied. The hydrolysis of urea by urease enzymes yields ammonium carbonate, raising the pH and leading to ammonia volatilization. The losses via this mechanism may be substantial on calcareous soils. Harmsen (1984) concluded from ^{15}N balance studies on the soils of northwest Syria that ammonia volatilization is probably the major loss mechanism since leaching and denitrification seldom occurred in that semiarid climate. The rate of loss is dependent not only on the chemistry of the surface soil, but highly dependent on the prevailing moisture and temperature conditions. Stumpe and Monem (1986) have indicated that losses can be substantial with very small inputs of rainfall. Larger rainfall events tend to move urea from the surface layer of the soil and its subsequent hydrolysis at depth leads to smaller losses due to ammonium adsorption. Nitrogen losses via ammonia volatilization are not necessarily confined to high pH soils. Bacon et al., (1986) reported losses of up to 35 kg N/ha within 5 days of urea application to an acid (pH 5.3) soil in a wheat growing area. Partial burial of urea reduced losses by 80%.

In the various data sets obtained for developing and testing of the model (see Chapter 5), it was perceived that N losses due to ammonia volatilization would have been small. This was because in most cases the fertilizer was incorporated or drilled before or at planting and that in most cases urea was not used. There are, of course, numerous instances in common fertilizer practice where ammonia volatilization may be a source of substantial loss. As well as the use of urea cited above, certain conditions under which anhydrous ammonia is used could lead to losses. A review of these losses from various sources has been given by Terman (1979). Since the majority of the fertilizer N consumed in the world is as urea (Stangel, 1984), and since anhydrous ammonia and UAN (urea ammonium nitrate) are becoming common fertilizers for wheat production (Russel, 1984), routines to simulate this process would be a worthwhile addition, provided it did not add greatly to the complexity or input data requirements of the model. Concomitant with this should be added procedures for the hydrolysis of urea and the capability for urea to be transported in the soil.

Several models of ammonia volatilization exist or form parts of other models. The PAPRAN model of Seligman and van Keulen (1981) approached this rather complex process by simply assuming that a constant proportion of ammonium present in the top layer of the soil will be lost. By their own admission this method has some shortcomings. More recently the problem has been approached with mechanistic models by Koelliker and Kissel (1985) and Rachhpal-Singh and Nye (1986a and b). This latter model is concerned only with losses following urea applications and consists of continuity equations describing the diffusion and reaction of urea, ammoniacal-nitrogen, and soil bases. It also describes the acidification of the soil surface following ammonia volatilization and a carbon dioxide profile in the soil due to urea hydrolysis and soil respiration. The model requires a large number of soil specific input coefficients, is complex, and the approach used would not lend itself to ready addition to the CERES-WHEAT-N model.

Other workers (Parton et al., 1981; Reddy et al., 1979; and Sherlock and Goh, 1983) have been concerned with modelling the loss of ammonia from urine patches or from animal waste applied to soils. These models generally consider the hydrolysis of urea, the equilibrium between ammonia and ammonium in the soil solution, the adsorption/desorption equilibrium of ammonium between soil solution and soil colloids, and the flux of ammonia to the atmosphere as indicated in the flow diagram from Parton et al. (1981) (Figure 8.1). These models also require the input of several soil and site specific constants and to date lack generality. Myers (1974 and 1986) claims there should be sufficient information in existence to model the process simply. A simplified general model is sorely needed.

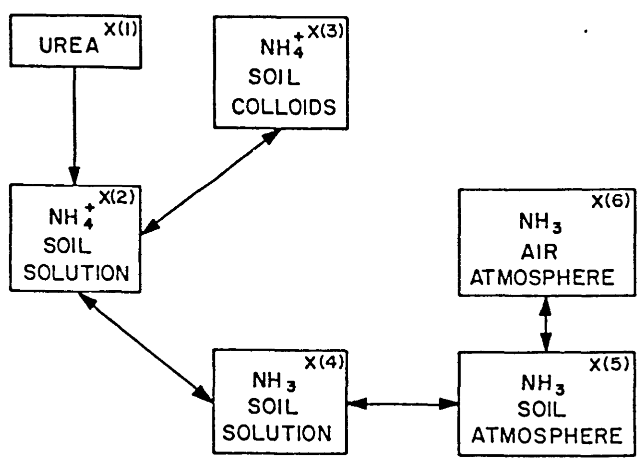

Figure 8.1. Schematic Outline of Components for an Ammonia Volatilization Model. (From Parton et al., 1981).

As a first step toward development of such a component to add to the CERES-WHEAT-N model, a preliminary model of urea hydrolysis has been formulated. The model is driven by a maximum hydrolysis rate estimated from other soil properties (primarily organic carbon and pH) which is scaled down according to the prevailing moisture and temperature conditions. Data to estimate the maximum hydrolysis rate have been drawn from several laboratory studies (Tabatabai and Bremner, 1972; McGarity and Myers, 1967; Myers and McGarity, 1968; Zantua et al., 1977; Dalal, 1975; and Beri and Brar, 1980). In each of these studies, incubations were performed at 37°C and at adequate moisture. Functions to scale this maximum rate according to the prevailing soil temperature and moisture conditions were estimated using the data presented by Vlek and Carter (1982).

Another common fertilizer practice, which the model does not specifically address, is that of banding or point placement of fertilizer. To simulate these cases with the current version of the model, the assumption has to be made that the fertilizer is uniformly incorporated in a layer at the depth of placement. While it is a fairly simple procedure to adjust layer thickness in the model input structure, the horizontal placement effect, where a band of fertilizer is applied say between the rows of a crop, is not so readily accomplished. One approach to this problem may be to examine the proportion of soil influenced by the fertilizer band. As time progresses the width of the fertilizer band, and hence this proportion, would be increased and the concentration within the band decreased as diffusion or flux from the band occurred. Changing the proportions in the affected and unaffected areas could then be accomplished daily if an approximation to the rate of movement from the band could be gleaned. In many cases the sensitivity of the model to this effect would probably be small. In some cases, such as when an application to a wide row spaced crop is made and at a dry time, sensitivity would be higher. Since wheat is not generally grown as a wide row crop, this would probably not be a worthwhile addition but may be considered for the CERES-MAIZE model. Kruh and Nunez (1982) report a simple procedure for modelling the effect of fertilizer banding which may be adaptable to the CERES model. Myers (1986) has also reported capability for simulating the effect of banding of fertilizer in a version of SORGF model.

Other possible modifications to the soil N components of the model which may add to its versatility and perhaps lead to improved simulation as briefly mentioned in Chapter 3 would be to examine the possibility of adding alternative leaching procedures. One for sandy soils and one for more structured soils. An internal switch triggered by the clay content of the soil could determine which routine was used in each simulation.

These procedures and those for ammonia volatilization would add to the complexity of the model and in some cases require further inputs. The tradeoff between these additions and improvements in model performance and/or versatility would need to be examined.

8.2.2. Plant N Components

The model currently makes no attempt to adjust the phenology of the crop according to its nutrient status. Some of the test data sets (notably Garden City, 1982) had noticeable effects of fertilizer rate on crop growth duration (high N delayed maturity by up to 6 days).

One explanation for this phenomenon is that the increased canopy growth associated with a higher N rate in some way may contribute to a cooler meristem either through greater shading or via greater transpiration. These mechanisms have also been proposed by Davidson and Campbell (1982) to help explain delayed maturity with high rates of N fertilizer on wheat varieties in Canada. Since the model utilizes ambient screen temperature rather than apical temperature to establish the growth durations, direct modelling of these effects would be difficult. Alternative approaches, possibly using a factor derived from NFAC to slow down the rate of degree day accumulation, could be employed. This could operate in a manner analogous to the photoperiod and vernalization indices used to slow down the rate of development during growth stage 1. Angus and Moncur (1982) have reported a similar method to do this based on data from controlled-environment experiments. It should be stressed, however, that the observed effects of excess N on growth duration are not usually large and thus the errors incurred in modelling crop growth without a nutritional effect on development are likely to be small.

As mentioned in Chapter 5 in some cases the simulations of grain protein percentage were poor. Addition of a further genotypic coefficient may help. The coefficient could be formulated such that it would be in the form of a 1 to 5 scale with a 5 used for cultivars with a consistently high grain protein concentration and 1 for low protein cultivars. Some restructuring of the code to enable a change in slope of the grain N accumulation rate as a function of the genetic coefficient would be required. Cox et al. (1986) have examined the genetic variation for nitrogen translocation in relation to grain yield and protein content. They had difficulty establishing relationships between translocation rate and translocation efficiency (N translocation/N assimilation prior to anthesis) and grain protein concentration. This suggests that the genotypic effect would not be a simple effect to capture within the model. It may be advantageous, however, to attempt a simple modification to the grain N accumulation routine to more closely mimic the differences between high and low cultivars.

Model development is a dynamic process. As applications arise or new problems are identified as a result of ongoing testing, modifications can be made. In this continuing process, priorities for further development must be addressed according to need. Small improvements could undoubtedly be made in some of the areas identified, but experience suggests that at this stage of development this improvement will come only with the investment of large amounts of time. Pragmatism thus demands use of the model within the limits recognized and acknowledged.

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