

SIMULATION OF NITROGEN DYNAMICS IN WHEAT CROPPING SYSTEMS

by

Douglas Charles Godwin

A Thesis Submitted to the University of New England
in Fulfillment of the Requirements for the Degree
of DOCTOR OF PHILOSOPHY

June 1987

ERRATA

Page 10, line 24--Various loss processes.

Page 22--Equation dy/dx should read dY/dX .

Page 23--Equations should have X rather than x.

Page 28--Replace last sentence with:

"Since crop yield is an input to these models, they cannot be used to describe response to fertilizer but they can be used to provide a prescription for fertilizer amount."

Page 31--Last sentence, which is continued on page 32, replace with:

"Since these models are driven by daily weather data they should, in principle, have the capacity to account for yield and response variations from year to year."

Page 32--Equation:

Replace w with W on left hand side of equation and in sentence above equation.

Page 32, line 22--.... as a ratio of an actual

Page 34--Delete second sentence.

Page 35, line 23--(Hanks and Ritchie, 1988).

Page 36, line 16--.... a function of soil nutrient

Page 42--Delete last sentence, paragraph 2.

Page 42, line 23--.... theory and/or solution of systems of simultaneous

Page 43, line 22--.... The minimum data set (MDS) for rice

Page 44, paragraph 1--Add the following sentences at end of the paragraph:

"Most of the models listed in Table 2.3 have been subjected to limited testing while some have had no testing. Those which had limited testing are indicated by an "L" under the testing heading and those with no reported testing are indicated by "0"."

Page 45, table 2.4--Caption should read $y = ax+b$.

Page 45, line 2--Model with the simulated mass of nitrate for the upper 60 cm.

Page 49, line 11--Insert reference as follows:

The original version of the model (Ritchie and Otter, 1985) had no nitrogen component.

Page 51, paragraph 2--Should appear as paragraph 1, page 53 immediately prior to section 3.2.

Page 56, figure 3.2c--Add an arrowhead coming into the WATBAL box from the Water Balance decision diamond.

Page 88, paragraph 1--Add the following sentence at the end:

"For a more detailed description of the temperature model, the reader is referred to Williams et al, (1984)."

Page 89, line 18--The original CERES-WHEAT model (Ritchie and Otter, 1985) was developed

Page 93--At the end of the first paragraph, add the following sentence:

"Critical N concentration refers to N concentration in the above-ground vegetative parts of the plant."

Page 178, line 10--.... data with statistical properties

Page 235, line 11--.... by the CERES-WHEAT model without the nitrogen components was the

Page 276--Delete the first paragraph.

Bibliography--Add Richardson, C. W., and Wright, D. A. (1984). WGEN: A model for generating daily weather variables. U. S. Department of Agriculture, Agricultural Research Service, ARS-8, 83 p.

Table of Contents

	<u>Page</u>
Acknowledgements	iii
Statement of Authenticity	vi
Abstract	vii
List of Tables	xii
List of Figures	xiv
List of Appendixesxviii
1. INTRODUCTION	2
1.1. Introduction and Research Perspectives	2
1.2. Historical Perspective and Thesis Overview	9
2. MODELLING N DYNAMICS IN CROPPING SYSTEMS	11
2.1. Systems Simulation and Modelling Overview.	13
2.2. Fertilizer Response and Response-Weather Models.	22
2.3. Crop Growth Response Models.	31
2.4. Nitrogen Dynamics Models	38
2.5. Statement of Model Requirements and Conclusions.	46
3. DESCRIPTION OF THE MODEL AND APPROACHES TO MODELLING N DYNAMICS	48
3.1. Overview	49
3.2. Water Balance.	53
3.3. Nitrate Flux	61
3.4. Soil Nitrogen Transformations.	66
3.5. Soil Temperature	86
3.6. Phasic Development	89
3.7. Plant Critical N Concentrations and N Deficit Factors.	93
3.8. Nitrogen Uptake.	99
3.9. Crop Growth.	107
3.10. N Redistribution During Grain Growth and Grain N Determination.	109
4. VALIDATION OF THE MODEL.	115
4.1. Validation Procedures.	116
4.2. Description of the Testing Data Base	125
4.3. Validation	132
4.4. Response to N in Individual Data Sets.	142
4.5. Seasonal Patterns of Biomass and N Uptake Accumulation	154
4.6. Seasonal Patterns of Nitrogen Balance.	167
4.7. Conclusions.	171
5. EVALUATION OF A WEATHER SIMULATOR FOR GENERATING DAILY WEATHER VARIABLES.	176
5.1. Model Requirements for Weather Data.	177
5.2. Nature of Australian Climates.	178
5.3. General Structure and Review of Weather Generators	181
5.4. Data and Programs Used to Evaluate the Richardson Weather Simulator.	194
5.5. Evaluation of the Simulator.	208
5.6. Examination of Length of Record Used	229
5.7. Discussion and Conclusions	232

Table of Contents
(Continued)

	<u>Page</u>
6. SENSITIVITY ANALYSIS.	236
6.1. Introduction and Principles of Sensitivity Analysis .	237
6.2. Examination of Key Coefficients	239
6.3. Sensitivity to Fertilizer Rate and Timing	266
6.4. Sensitivity to Soil Physical Properties	272
6.5. Sensitivity to Depth of Placement	273
6.6. Sensitivity to Nitrification Inhibition	283
6.7. Conclusions	286
7. MODEL APPLICATIONS IN FERTILIZER STRATEGY EVALUATION. . . .	288
7.1. Introduction to Risk Analysis	289
7.2. Strategy Selection Under Uncertainty.	290
7.3. Description of the Simulation Study	295
7.4. Results and Interpretation.	300
7.5. Conclusions	309
8. CONCLUSIONS	313
8.1. General Conclusions on the Utility of the Model . . .	314
8.2. Areas for Further Study	315
Bibliography	323
Appendices	

Acknowledgments

When undertaking a project such as this, spanning several disciplines and working in three quite different research institutes, one accrues many debts.

Before specifically nominating those due for special thanks I would like to mention that my initial interest in crop modelling and the potential it held as a new science was originally kindled in 1974 as an agronomy undergraduate in a series of lectures provided by Dr. R.C.G. Smith, now of CSIRO Griffith. My interest was later developed further during postgraduate study in agricultural economics with Professor Jock Anderson of the University of New England. I wish to thank these two excellent teachers for providing the initial motivation for launching my career in the direction it has taken.

The financial support during the course of the project from the International Fertilizer Development Center (IFDC), Muscle Shoals, Alabama, and from the United States Department of Agriculture (USDA) via a collaborative agreement between the Cropping Systems Evaluation Unit at Temple, Texas, and IFDC is gratefully acknowledged. Partial funding for a 1-year study leave to UNE was provided by the University of New England. I am indebted to the Department of Agronomy and Soil Science at UNE for securing these funds to make the study leave possible.

I owe a very special debt of gratitude to Dr. Joe Ritchie, currently Homer Nolan Chair at the Institute for Water Research,

Michigan State University, and formerly of USDA, Temple, Texas, for his advice, encouragement, patience, and humanity during every phase of the project. Dr. Paul Vlek, Director of the Agro-Economic Division, IFDC, provided excellent scientific and administrative support throughout the project. His very constructive review during all stages of the project was very valuable. Dr. Hazel Harris of International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria, formerly from UNE, very capably provided direction and review during my period of study leave at UNE and during the period of thesis preparation and assisted with the massaging of some of the meteorological data. Dr. Ian Johnson, Agronomy Department, UNE, also provided valuable comments on the manuscript.

Much gratitude is also owed to:

1. Dr. Allan Jones, Crop Physiologist, USDA, Temple, Texas, for sharing of ideas and concepts and many hours of enjoyable brow beating during the early days of model development.
2. Dr. Clarence Richardson, Hydrologist, USDA-SCS, Temple, Texas, for allowing me to tinker with his weather simulator programs.
3. Dr. Julio Henao, Biometrician, IFDC, for many fruitful discussions on appropriate procedures for testing various models.
4. Those scientists who provided the data required to run the model against data sets used in model development and testing, specifically, Dr. C. A. Campbell (Agriculture Canada), Dr. D. Kissell (Kansas State University), Dr. M. Hooker (USDA, Kansas), Dr. M. Mason (WA Dept. of Agriculture, Western Australia), Dr. M. Stapper

(CSIRO, formerly of ICARDA, Syria), Dr. Gillian Thorne (AFRC, Rothamsted, UK), Dr. J.H.J. Spiertz (CABO, Wageningen, Netherlands), Dr. R. Storrier (Riverina College of Advanced Education, Wagga Wagga, NSW Australia), Dr. M. Wagger (North Carolina State University, previously Kansas State University, Dr. J. Caprio (USDA, Bozeman, Montana), Dr. B. Klepper (USDA, Pendleton, Oregon), and Dr. A. Bauer (USDA, Mandan, North Dakota).

5. The Australian Bureau of Meteorology for provision of meteorological data.
6. The staff of the IFDC nitrogen program who were able to provide valuable feedback in the early days of model development.
7. The support staff of IFDC and the Blackland Research Center in Temple, Texas, for very able technical assistance when needed and, in particular, Mr. Tom McCafferty for assistance with programming.

I wish also to thank my wife who assisted in transcribing some of the earlier drafts and who, together with my children, were always patient throughout the project despite being moved across countries and continents several times and who provided the necessary continuous moral support.

Abstract

Some 8 million tonnes of fertilizer N are applied annually to the world's wheat crop. The efficiency with which this is used is very variable but in general poor. Much of this variability in fertilizer efficiency and hence crop response to N is due to differences in climate. Soil physical and chemical properties, crop residues, crop variety, and management practices also influence crop response to fertilizer and efficiency. A tool which is able to reliably predict crop response to N and determine the causes and magnitude of poor fertilizer recovery could greatly assist crop and fertilizer management. Various approaches to describing the response to N and their ability to capture the effects noted above are reviewed in the thesis. The shortcomings of traditional response research are highlighted and dynamic computer simulation modelling is advanced as an appropriate methodology. A review of modelling methodologies and models of N dynamics in cropping systems is presented. The review indicated that one comprehensive model with a management or user focus and which is able to accommodate the effects of the factors listed above is lacking.

This thesis describes the CERES-WHEAT model and the development of an N component for it. This model utilizes a daily time step and is designed to be able to simulate the growth, yield, and response to N of a wheat crop grown anywhere in the world. The model requires daily climatic data as well as data describing soil water storage characteristics and data pertaining to soil factors which influence

the supply of N to the crop. The model utilizes several genotype specific coefficients to characterize a cultivar's response to environment. Management data defining the time of planting, plant population, fertilizer rate, source, and time of application are also required. The CERES-WHEAT model describes the processes of evapotranspiration, soil water balance, crop ontogeny as affected by temperature, photoperiod, and vernalization, and the growth of leaves, stems, roots, ears, and grain. The nitrogen component of the model adds to this the description of mineralization and/or immobilization of N associated with the decay of crop residues, mineralization of "stable" organic matter, movement of nitrate in the profile, nitrification, denitrification, uptake of N by the plant, plant N effects on growth processes, and redistribution of N within the plant associated with grain filling. The derivation of the functions for each of these processes and their relationship to published information is described.

To validate the model, data sets from field experiments on wheat from various locations in the world were assembled. These data sets encompassed a broad range of climatic environments, crop cultivars, soil conditions, fertilizer rates, and management practices. Simulated yield, biomass, total N uptake, grain N uptake, and N balance compared favorably with observations. The statistical techniques available for simulation model validation were reviewed and validations compared using various techniques.

Weather simulation techniques were reviewed and as a prelude to long-term simulations the WGEN stochastic weather simulator program

was evaluated. Long-term daily rainfall and temperature data for many sites in the Australian wheat belt were assembled and used to calculate coefficients for the WGEN weather simulator. Long sequences of daily weather data for each location were synthesized using these coefficients and the WGEN simulator. Rainfall synthesis performance aspects of WGEN were assessed by comparing predicted and observed values of several parameters. These parameters were daily and monthly rainfall amount, rainfall frequency, wet spell length, dry spell length, and the frequency of large rainfall events. Similarly the validity of synthesized temperature data were examined by comparing predicted and observed mean maximum and minimum temperatures, temperatures on wet and dry days, and the occurrence of temperature extremes. WGEN was able to produce sequences of daily weather data statistically similar to observed sequences at most locations. Exceptions to this occurred when the length of run used to characterize the parameters was short.

Several sensitivity analyses of the CERES-WHEAT model were performed. The first of these involved running the model coupled to WGEN at Rothamsted (UK), Wichita (Kansas, U.S.A.), and Wongan Hills (W.A., Australia). In this analysis key variables were perturbed up and down 5%, 10% or 20% and the model run with 20 years of simulated climatic data. Results from a run with a variable perturbed were compared to a standard run with no variables perturbed. Runs were made both with a moderate fertilizer rate and with no fertilizer applied. Differences in simulated grain yields, biomass, and N uptake

were used as indices of sensitivity. The analysis showed daily rainfall to be the most sensitive parameter. Other sensitive parameters were temperature, solar radiation, variables affecting soil moisture availability, and when no fertilizer was applied certain variables which affect the supply of N to the crop were sensitive. Sensitivity varied among the three sites. Other sensitivity analyses were conducted to examine the model's sensitivity to fertilizer rate, timing, placement, and to nitrification inhibition. To examine sensitivity to fertilizer rate and timing, data from a fertilizer timing experiment on a coarse sand in Western Australia were used as the basis for a reference simulation. Combinations of fertilizer rates, split-application patterns, and times of application illustrated sensitivity to these management options and enabled identification of treatments where losses were minimized and grain yields were maximized. Sensitivity to depth of placement was investigated using 20 years of simulated climatic data for Jondaryan (QLD, Australia) and Waite Institute (SA, Australia). The range of responses in simulated grain yield to deep placement of fertilizer compared to surface incorporation of fertilizer was much greater at Jondaryan than at the Waite Institute. The nature and magnitude of the response to simulated deep placement was very seasonally dependent. Sensitivity to nitrification inhibition was examined using a sequence of simulated weather data for Rothamsted and comparing a simulation run with nitrification blocked for 30 days following a fertilizer application with a control run with nitrification not inhibited. In most years the simulated inhibition reduced simulated

leaching and denitrification losses but the resulting savings contributed only slightly to improved fertilizer recovery and had little impact on grain yield.

The simulated growth of wheat crops and the response to various fertilizer strategies was examined in three locations forming a north-south transect and three locations forming an east-west transect of the eastern Australian wheat belt. Each fertilizer strategy was compared to a reference simulation using 50 years of simulated daily weather data. Risk analysis procedures incorporating the principles of stochastic dominance were used to evaluate the strategies. Simulated losses at each location were usually small and the response to N determined by the availability of water. With the given initial conditions, the analysis determined appropriate N rates and also suggested that possibilities for improving N fertilizer efficiency in these locations via changes in fertilizer management were usually limited.

List of Tables

	<u>Page</u>
1.1 Total Amount of Nitrogenous Fertilizer Consumed in Australia, United Kingdom, and the World	2
2.1 Summary of Some Multiple Regression Models Relating Yield or Nitrogen Requirement of Cereals to Soil and Climatic Factors.	27
2.2 Some Published Dynamic Simulation Models for Cereal Crops.	36
2.3 A Compilation of Simulation Models of Nitrogen Dynamics in Cropping Systems.	40
2.4 A Comparison of Six Soil N Dynamics Simulation Models.	45
3.1 A Classification of Deterministic Leaching Models.	62
3.2 Growth Stages of Wheat as Defined in CERES-WHEAT	90
3.3 Functions Used for Converting From Fractional Growth Stage (XSTAGE) to Zadoks' Growth Stage (ZSTAGE).	91
3.4 Data Sources Used for Determination of Critical N Concentration Relationships.	95
3.5 Stress Factors Used to Modify Plant Growth Processes in CERES-WHEAT	109
4.1 Summary Measures for all Data Sets	133
4.2 Effect of Errors in N Uptake Simulation on Errors in Simulated Apparent Recovery.	141
5.1 Studies Employing a Markov Chain Technique for Predicting Rainfall Occurrence.	184
5.2 Locations Used for Development and Testing of Rainfall Generator Parameters and Subsequent Testing.	195
5.3 Locations Used for Calculation of Weather Generator Parameters for Temperature and Solar Radiation	197
5.4 Values of "T" for Maximum and Minimum Temperatures on Wet and Dry Days	205
5.5 Comparison of Observed and Simulated Rainfall Parameters for Bathurst	212
5.6 Comparison of Observed and Simulated Rainfall Parameters for Biloela.	213
5.7 Comparison of Observed and Simulated Rainfall Parameters for Clare.	214
5.8 Comparison of Observed and Simulated Rainfall Parameters for Cobar.	215
5.9 Comparison of Observed and Simulated Rainfall Parameters for Geraldton.	216
5.10 Comparison of Observed and Simulated Rainfall Parameters for Temora	217
5.11 Comparison of Observed and Simulated Rainfall Parameters for Quirindi	218
5.12 Comparison of Observed and Simulated Rainfall Parameters for Rutherglen	219

List of Tables
(Continued)

	<u>Page</u>
5.13 Comparison of Observed and Simulated Dry Spells for Selected Locations	224
5.14 Comparison of Observed and Simulated Temperature Parameters	225
5.15 Number of Months Where Generated Mean Monthly Rainfall Was Significantly Different From the Long-Term Observed Mean Monthly Rainfall.	231
6.1 Initial Conditions and Resultant Means Used in Sensitivity Analysis Simulations	240
6.2 Variables Examined in a Sensitivity Analysis of the CERES-WHEAT Model.	243
(a) Model Input Variables.	
(b) Variables Pertaining to the Nitrogen Components of the Model.	
6.3 "S" Values for Yield Sensitivity Determined From Regression of Mean Yield Response on Perturbation Percentage for 26 Variables When Fertilizer Was Applied.	249
6.4 "S" Values for Yield Sensitivity Determined From Regression of Mean Yield Response on Perturbation Percentage for 26 Variables When Fertilizer Was Not Applied.	250
6.5 "S" Values for Biomass and N Uptake Sensitivity From Regression of Response on Perturbation Percentage for 26 Variables When Fertilizer Was or Was Not Applied	253
6.6 Effect of Temperature Perturbation on the Simulated Mean Duration of Crop Growth.	260
6.7 Soil Water Input Data Used in Sensitivity Analysis	275
6.8 Mean Percentage Variation From Surface Incorporation in Yield, Biomass, N Uptake, and Apparent Recovery of Fertilizer for Various Depths of Placement	279
7.1 Fertilizer Application Patterns Used in the Simulation Study.	298
7.2 Simulated Rainfall and Yield Ranges at Five Sites in the Simulation Study.	302

List of Figures

	<u>Page</u>
1.1 Relationship Between Cereal Grain Yield and Rate of Nitrogen Fertilization Over the Past 25 Years.	4
1.2 World N Production and Consumption	4
2.1 Schematic Presentation of the Nature of Model Content for Five Types of Model Which Describe Response to Fertilizer and a Summary of Model Characteristics	20
2.2 The Basic Steps of Systems Simulation.	21
2.3 Schematic Representation of the Mitscherlich Response Function	24
2.4 Tests of the Myers (1984) Model for Winter Wheat Using Data From Nebraska, Kansas, and South Australia.	30
3.1 Systems Diagram of the CERES-WHEAT Model	50
3.2 Flowchart for the CERES-WHEAT Simulation Model	54
(a) Input Selection Routines.	
(b) Initialization Routines.	
(c) Subroutines for N Transformations, Water Balance, and Leaching.	
(d) Subroutines for Crop Growth, Phasic Development, Response to Cold Temperature, Response to N, and N Uptake.	
(e) Output Routines.	
3.3 Flowchart of the Drainage Component of the Water Balance Subroutine (WATBAL) in the CERES-WHEAT Model	60
3.4 Effects of Soil Moisture on Nitrogen Transformation Rates.	74
3.5 Effect of Carbon:Nitrogen Ratio on Residue Decomposition Rates.	76
3.6 Effect of Soil Temperature, Soil Water, and Residue Addition on Predicted Denitrification Rate	87
3.7 Critical Concentrations of N in Plant Tops for:	96
(a) Winter Wheat.	
(b) Spring Wheat.	
3.8 Relationship Between NFAC and the Nitrogen Deficit Factors (NDEF1, NDEF2, NDEF3, NDEF4)	99
3.9 Simulated Effect of Changing Soil Water Status on Potential Uptake of Nitrate From a Layer	104
3.10 Relationship Between Calculated Daily Thermal Time and the Rate of N Accumulation in Wheat Kernels.	111
3.11 Effect of Maximum and Minimum Temperatures on the Simulated Rate of Grain N Accumulation	113
4.1 Comparisons of Predictions of the CERES-WHEAT Model With Observed Data From Experiments	134
(a) Grain Yield.	
(b) Biomass.	
(c) Kernel Weight.	
(d) Grains Per Meter Square.	
(e) N Uptake at Maturity.	
(f) Grain N Uptake.	
(g) Anthesis N Uptake.	
(h) Grain Protein Percentage.	

List of Figures
(Continued)

	<u>Page</u>
4.2 Comparison of Predicted and Observed Grain Yield Response to Applied N in Individual Data Sets.	143
4.3 Comparison of Predicted and Observed Grain Yield Response to Differing Fertilizer Split Application Patterns.	151
4.4 Comparison of Predicted and Observed Grain Yields at Differing Fertilizer Rates for Three Varieties With Different Irrigation Strategies	152
4.5 Comparison of Predicted and Observed Grain Protein Response to Applied N in Individual Data Sets.	155
4.6 Comparison of Predicted and Observed Seasonal Dry Matter Production for Individual Data Sets	162
4.7 Comparison of Predicted and Observed Seasonal Patterns of N Uptake for Individual Data Sets	168
4.8 Comparison of Observed and Predicted Values of "Accountable N"	172
4.9 Comparison of Predicted and Observed Patterns in Seasonal N Balance for Individual Data Sets.	173
5.1 Percentage Mean Variability From Annual Mean Rainfall for Locations in Australia.	180
5.2 Isotherms for Southern Australia.	182
(a) January Maximum Temperature.	
(b) July Minimum Temperature.	
5.3 Observed Frequency Distribution of Rainfall Amounts on Rainy Days at Kano, Nigeria	187
5.4 Locations Within the Australian Wheat Belt Used for the Development of the Weather Generator Parameters and Subsequent Testing.	199
5.5 Comparison of Observed and Simulated Monthly Rainfall	210
5.6 Comparison of the Coefficient of Variation for Monthly Rainfall Amount Calculated From Observed and Predicted Rainfall at Biloela and Geraldton	220
5.7 Comparison of Observed and Simulated Rainfall Per Rainy Day for Eight Locations	222
5.8 Comparison of Observed and Simulated Monthly Mean Maximum and Minimum Temperatures on Dry Days at Six Locations	228
6.1 Figure Illustrating the Hypothetical Range of Simulated Effects on Yield When a Model Variable is Perturbed	247
6.2 Range and Frequency of Yield Outcomes as the Result of Perturbations of Various Variables.	248
(a) Input Variables at Wongan Hills.	
(b) Input Variables at Wichita.	
(c) Input Variables at Rothamsted.	
(d) N Variables at Wongan Hills.	
(e) N Variables at Wichita.	
(f) N Variables at Rothamsted.	

List of Figures
(Continued)

	<u>Page</u>
6.3 Simulated Nitrate Losses From the Bottom of the Soil Profile at Lancelin	269
6.4 Simulated Grain Yield Response to Various Fertilizer Split Application Strategies at Lancelin.	270
6.5 Simulated Flux of Nitrate From a Layer 15 cm Deep at Lancelin.	271
6.6 Simulated Yield Response to Basal Applications of Fertilizer at Lancelin on Three Soil Types.	274
6.7 Simulated Yield Response to Split Applications of Fertilizer at Lancelin on Three Soil Types.	274
6.8 Range of Responses in Simulated Grain Yield to Depth of Placement of Fertilizer on a Vertisol at Jondaryan.	280
6.9 Range of Responses in Simulated Grain Yield to Depth of Placement of Fertilizer on an Alfisol at Jondaryan.	280
6.10 Range of Responses in Simulated Grain Yield to Depth of Placement of Fertilizer on a Vertisol at Waite Institute.	282
6.11 Range of Responses in Simulated Grain Yield to Depth of Placement of Fertilizer on an Alfisol at Waite Institute.	282
6.12 Simulated Effect of Nitrification Inhibition at Rothamsted, England	285
7.1 Hypothetical Yield Responses to Applied Fertilizer.	291
7.2 Variation in Simulated Yield and Response to Fertilizer Over a 50-Year Period at Dubbo.	291
7.3 Cumulative Probability Density Function for Simulated Grain Yield Response to Three Fertilizer Strategies at Dubbo	291
7.4 Illustration of First Degree Stochastic Dominance (FSD)	293
7.5 Illustration of Second Degree Stochastic Dominance (SSD) Where CDF's Cross Twice	294
7.6 Cumulative Probability Density Function for Simulated Grain Yield Response to Five Rates of N Fertilizer at Five Locations.	301
7.7 CDF for Nitrate Leaching From a Layer 50 cm Deep When 60 kg N/ha was Applied at Planting at Orange.	305
7.8 CDF's for Apparent Recovery of Fertilizer at Orange, Dubbo, and Trangie When 60 kg N/ha was Applied at Planting.	305
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.	307
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.	307
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.	307
7.12 CDF's for Water Stress Occurring in Stage 5 at Orange When Various Rates of Fertilizer are Applied.	307

List of Figures
(Continued)

	<u>Page</u>
7.13 CDF's for Yield Advantages to Split or Delayed Applications of Fertilizer at Orange	308
7.14 CDF's for Yield Advantages to Split or Delayed Applications of Fertilizer at Rutherglen	308
7.15 CDF's for Yield Advantages to Split or Delayed Applications of Fertilizer at Dubbo	308
7.16 SSD Functions for Three Fertilizer Strategies at Orange . . .	310
8.1 Schematic Outline of Components for an Ammonia Volatilization Model.	318

List of Appendixes

1. Listing of the CERES-WHEAT Model
2. Glossary of the Variables Used in CERES-WHEAT
3. IBSNAT Technical Report 5
4. Listing of N-Model Testing Data Base
5. FORTRAN Program (METBR) to Read Daily Rainfall Data and Calculate Conditional Probabilities, Parameters of the Gamma Distribution and Statistics on Observed Rainfall
6. Calculated Rainfall Generation Parameters for Locations in the Australian Wheat Belt
7. Sample Output From Program METBR for Bathurst
8. Sample Statistical Comparison of Observed and Generated Rainfall for Bathurst
9. Calculated Parameters for Temperature and Solar Radiation Data Generation
10. WGEN Program With Procedures to Compute Statistics on Generated Weather Data
11. Cross and Serial Correlation Coefficients for Daily Maximum and Minimum Temperature Calculated From the Observed Data

Table of Contents

	<u>Page</u>
<u>Chapter 1--Introduction</u>	
1.1 Introduction and Research Perspective	2
1.2 Historical Perspective and Thesis Overview	9