

**SIMULATION OF ENVIRONMENTAL AND VARIETAL
EFFECTS ON GROWTH AND YIELD OF AROMATIC
RICE USING CERES-RICE MODEL IN MIDDLE
GUJARAT AGRO-CLIMATIC REGION**

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**OF
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(AGRICULTURE)**

**IN
AGRICULTURAL METEOROLOGY**

**BY
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M. Sc. (Agri.)**

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ANAND AGRICULTURAL UNIVERSITY
ANAND - 388 110
2009**

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*Dedicated
To
My Late Grand Father*



Abstract

**SIMULATION OF ENVIRONMENTAL AND VARIETAL EFFECTS ON
GROWTH AND YIELD OF AROMATIC RICE USING CERES-RICE
MODEL IN MIDDLE GUJARAT AGRO-CLIMATIC REGION**

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ABSTRACT

Crop growth simulation models are useful tools for considering the complex interactions between a range of factors that affect crop performance, including weather, soil properties and management. In the present investigation, CERES-Rice v.3.5 model was used to develop genetic coefficients and validate it under Nawagam conditions by conducting a field experiment on Silty Loam soils during two consecutive *kharif* seasons of 2007 and 2008. The study was carried out for purposes of simulation of phenology, growth and yield of four different cultivars of aromatic rice (cv. Pankhali, Narmada, GR-104 and Pusa Basmati-1), validation of three dates of transplanting viz., D₁ (8th July), D₂ (22nd July) and D₃ (8th August), calibration of genetic coefficients of four different rice cultivars and to carry out the

sensitivity analysis of CERES-Rice model with respect to middle Gujarat agro-climatic region.

The genotype GR-104 yielded the highest irrespective of dates of transplanting among various cultivars of aromatic rice taken in the experiment during both crop years as well as on pooled data basis. The second date of transplanting, D₂ (22nd July) gave the highest yield in all the cultivars as compared to the yields realized from the treatments D₁ and D₃.

The association of simulated grain yield in case of cv. GR-104 was found in perfect agreement with the correspondingly measured grain yield of three dates of transplanting, when pooled over the years. While, the association between simulated and observed grain yields of Pankhali, Narmada and Pusa Basmati-1 cultivars were found satisfactory. The second date of transplanting (D₂) recorded highest above ground biomass production irrespective of cultivars during both the crop years and pooled basis. This result might be due to higher average bright sunshine hours encountered by the crop in D₂ transplanting than that of D₁ in crop season 2007 and D₁ and D₃ in 2008 along with other congenial weather conditions which favoured higher grain yield and straw yield. The overall trend of simulated above ground biomass production indicated overestimation by the model except for few treatments. However, positive significant association for all four different cultivars of rice was observed between simulated and observed biomass production during 2007, 2008 and for pooled data.

Perfect agreement between observed and simulated days to anthesis was recorded in D₂ transplanting for all genotypes except Narmada during crop season 2007. Where as, overall results showed that days to anthesis decreased treatmentwise irrespective of cultivars from first to third date of transplanting, both in case of observed and simulated values. More or less cv. GR-104 recorded highest mean error percent between simulated and

observed days to anthesis among four different cultivars of aromatic rice where as, cv. Narmada recorded the least mean error percent.

The measured as well as model simulated LAI was found maximum at the anthesis stage during both the years. The periodical as well as maximum values of LAI in all four genotypes of rice were highest in D₂ transplanting and lowest in D₃ under measured as well as simulated conditions during both the crop years.

The highest LAI was recorded in GR-104 in all the corresponding dates of transplanting than that of others. The performance of the model in simulating grains per square meter was found to have been better in 2007 than in rest of the periods. All the test criteria were observed to be better for 2007 than those corresponding ones for 2008. The results, however, indicated the weakness of the model in simulating grains per sq. meter. The results suggested that performance of the model in simulating grains per sq. meter for the crop-growing season of 2008 was poor. The observed and simulated values for grain number per panicle and their mutual association was good in 2007 in comparison with those for the rest of the period. The model was observed to have overestimated the number of grains per panicle for 2008 and also for the pooled data on a few occasions. The various test criteria showed that the overall performance of the CERES-Rice model in simulating the harvest index was found to be good.

CERES-Rice simulated grain yield under altered photoperiod indicated that the simulated yield increased linearly with incremental unit increase in day length and *vice versa*. The percentage change over base yield was highest recorded in the case of GR-104 and lowest in Pankhali genotype. Simulated grain yields were increased gradually in comparison with base yield with increase in solar radiation from 1 to 5 MJm⁻²day⁻¹ in case of Pankhali and GR-104; however genotype Narmada and Pusa Basmati-1 did not show such gradual increment up to increment of 5 MJm⁻² day⁻¹. In case of

gradual reduction in solar radiation, gradual decrease in yield in terms of per cent change from base yield was noted in all the four genotypes, but reduction was almost up to 50% was recorded in case of GR-104 cultivar.

Sensitivity of CERES-Rice model simulated grain yield to incremental units of maximum air temperature showed a gradual decrease in yield while the down scaled maximum temperature increased the yield in all four genotypes of rice. Maximum reduction in yield due to increment of same unit of maximum temperature was recorded in GR-104 genotype where as Pankhali recorded least reduction for corresponding temperature level. The highest percentage change in yield over base yield due to reduction of maximum temperature was recorded in Pusa Basmati-1 and least by the genotype GR-104. Such behavior of the model was mainly due to reduction in duration of anthesis and grain filling with rise in ambient temperature and *vice versa*.

Elevated levels of CO₂ by 370 and 410 ppm increased grain yields as simulated by the model by 3.3 to 27.9% in four different aromatic cultivars of rice when compared with base yield. Genotype GR-104 could be performed well among four different genotypes of rice under elevated scenario of CO₂ as it was recorded maximum positive change under elevated CO₂ concentration. Simulated grain yield was decreased in comparison with base yield when direct sowing method was applied in all the four genotypes of rice. Large yield reductions were observed on decreasing plant population up to 25 plants per sq. meter in all cultivars, but Pusa Basmati-1 recorded highest. However, model did not show any noticeable percentage change when compared with the base yield in relation to increasing the plant population from 75 to 200 per sq. meter. This showed the insensitivity of the model to varying plant population level. However, the model was found enough sensitive to account for the effects of transplant age of seedlings on simulated grain yield in comparison with the base yield.



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CERTIFICATE - I

Dated : 17 / 06 /2009

This is to certify that **MOHAMMAD SHAMIM** has successfully completed the comprehensive examination of major and supporting subject on 03 / 01/ 2009 as required under the regulation for Ph.D. in Agriculture.

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CERTIFICATE - II

Dated : 17 / 06 /2009

This is to certify that the thesis entitled “**Simulation of environmental and varietal effects on growth and yield of aromatic rice using CERES-Rice model in middle Gujarat Agro-climatic region**” submitted for the degree of **Doctor of Philosophy** in the subject of **Agricultural Meteorology** embodies bonafide research work carried out under my guidance and supervision and that no part of this thesis or research work has been submitted for any other degree. The assistance, guidance and help received during the course of investigation have been fully acknowledged. The draft of the thesis was also approved by advisory committee on 17/06/09.

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CERTIFICATE - III

Dated : 17 / 06 /2009

This is to certify that the thesis entitled “**Simulation of environmental and varietal effects on growth and yield of aromatic rice using CERES-Rice model in middle Gujarat Agro-climatic region**” submitted by **Mohammad Shamim** to the Anand Agricultural University, Anand in the partial fulfillment of requirement for the degree of **Doctor of Philosophy** in Agriculture in the subject of **Agricultural Meteorology** after suggestion and recommendation by external examiner was discussed and defended by the candidate before the following members of the advisory committee. The performance of the candidate in the oral examination on this thesis has been found satisfactory; we therefore, recommended that the thesis may be approved.

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DECLARATION

This is to certify that whole of the research work reported in the thesis in partial fulfillment of the requirement for the award of the degree of **Doctor of Philosophy** in Agriculture in the subject of **Agricultural Meteorology** is the result of investigation done by undersigned under the direct guidance and supervision of **Dr. A.M. Shekh, Principal and Dean**, Anand Agricultural University, Anand and no part of the research work has been submitted for any other degree so far.

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Anand
June 17th, 2009

(MOHAMMAD SHAMIM)

CONTENT

Head No.	Title	Page No.
I. INTRODUCTION		
1.1	Rice	1
1.1.2	Aromatic rice and its characteristic features	4
1.1.3	Area and production of rice crop	5
1.1.4	Aromatic rice growing regions	7
1.1.5	Status of rice production and its requirement by 2030	8
1.1.6	Role of aromatic rice in the export earnings	11
1.1.7	Future prospects of aromatic rice	12
1.2	Crop growth simulation models	13
1.2.1	Origins and genesis of a crop growth simulation model	13
1.2.2	Brief description of CERES-Rice model	14
1.2.2.1	Phenology	14
1.2.2.2	Growth	15
1.2.2.3	Water balance	15
1.2.2.4	Soil organic mater and N dynamics	16
1.2.3	Applications of CERES-Rice model	17
II. REVIEW OF LITERATURE		
2.1	Effect of weather on growth and yield of rice	19
2.2	Effect of weather on phenology of rice	31
2.3	Effects of date of transplanting or sowing on growth and yield of rice	38
2.4	Crop growth models	48
2.4.1	Types of the model	48
2.5	Crop simulation models	50
2.6	Applications of crop simulation models	55
2.6.1	Yield forecasting	56
2.6.2	Yield gap analyses	56
2.6.3	Yield trend analysis	58
2.6.4	Devising agronomic management strategies	59
2.6.5	Extrapolation to other locations	61
2.6.6	Impacts of climate change on yield	62
2.6.7	Aiding government policy and strategic planning	70
2.7	Calibration of crop simulation models	71

Head No.	Title	Page No.
2.8	Evaluation of crop growth simulation modeling	75
2.8.1	Phenology	75
2.8.2	Grain and biomass yields and yield components	78
2.8.3	Growth	81
2.9	Sensitivity study of the crop simulation models	82
III. MATERIALS AND METHODS		
3.1	Experimental site	84
3.2	Climate	84
3.3	Microclimatic conditions prevailed during crop periods	85
3.4	Meteorological observations	85
3.5	Description of soil of experimental field	85
3.6	Crop and cultivar	87
3.7	Experimental details	90
3.8	Crop management practices	90
3.8.1	Land preparation	90
3.8.2	Application of fertilizers	91
3.8.2.1	For seed bed	91
3.8.2.2	For main field	91
3.8.3	Seed bed preparation and sowing of seeds	91
3.8.4	Transplanting and spacing	92
3.8.5	Cultural operations	92
3.8.5.1	Irrigation	92
3.8.5.2	Weeding and hoing	92
3.8.5.3	Control of pest and diseases	92
3.8.6	Harvesting and threshing	93
3.9	Crop assessment studies	93
3.9.1	Phenological observations	93
3.9.2	Crop growth observations	94
3.9.2.1	Leaf area index (LAI)	94
3.9.2.2	Above ground biomass	95
3.10	Growth, yield and yield components	95
3.10.1	Number of panicles	95
3.10.2	Number of grains/panicle	95

Head No.	Title	Page No.
3.10.3	Test weight	95
3.10.4	Grain yield	96
3.10.5	Straw yield	96
3.10.6	Harvest index (HI)	96
3.11	Statistical analysis	96
3.12	CERES- Rice model	97
3.12.1	Brief description of CERES- Rice model	98
3.12.2	Minimum data required for operation and evaluation of CERES-Rice model	99
3.12.3	Overview of CERES-Rice model operations	101
3.12.4	CERES-Rice input and output files	102
3.12.5	Modes of operation	104
3.12.5.1	Experiment directory file	104
3.12.5.2	Weather directory file	104
3.12.5.3	Soil properties directory file	104
3.12.5.4	Soil profile initial condition file	104
3.12.5.5	Irrigation management file	105
3.12.5.6	Fertilizer management file	105
3.12.5.7	Treatment management file	105
3.12.5.8	Crop cultivars directory file	105
3.12.5.9	Field observed data file	106
3.12.6	Running the crop model	106
3.12.6.1	Output file-1	107
3.12.6.2	Output file-2	107
3.12.6.3	Output file-3	107
3.12.6.4	Output file-4	107
3.12.7	Calibration of the CERES Rice model	107
3.12.8	Validation of the model	110
IV. RESULTS AND DISCUSSION		
4.1	Weather conditions during crop seasons <i>kharif</i> 2007 and 2008	112
4.1.1	Air temperature	112
4.1.2	Sunshine hours	114
4.1.3	Wind speed	115
4.1.4	Mean vapour pressure	115
4.1.5	Rainfall	116
4.2	Field experimental results	118
4.2.1	Effects on grain yield of rice crop	119
4.2.2	Effects on straw yields of rice crop	123
4.2.3	Effects on above ground biomass	126

Head No.	Title	Page No.
4.2.4	Inferences on the most effective combination of treatments for high yield	129
4.3	CERES-Rice simulation results	130
4.3.1	Grain yield	131
4.3.2	Above ground biomass	135
4.3.3	Periodic dry matter production	140
4.3.4	Phenological development	142
4.3.4.1	Days to anthesis	142
4.3.4.2	Days to maturity	148
4.3.4.3	Periodic leaf area index	152
4.3.4.4	Number of grains per square meter	155
4.3.4.5	Grain number per panicle	157
4.3.4.6	Test weight	158
4.3.4.7	Harvest index	159
4.3.4.8	Sensitivity analysis of CERES-Rice model to various weather and non weather parameters	159
4.3.4.8.1	Effects of photoperiod	160
4.3.4.8.2	Effects of solar radiation	161
4.3.4.8.3	Effects of maximum air temperature	161
4.3.4.8.4	Effects of minimum air temperature	162
4.3.4.8.5	Effect of elevated carbon dioxide	163
4.3.4.8.6	Effects of planting methods	165
4.3.4.8.7	Effect of transplant age of seedling	165
4.3.4.8.8	Effect of plant population	166
V. SUMMARY AND CONCLUSION		
5.1	General	167
5.1.1	Objectives and methodology	168
5.1.2	Calibration and validation of CERES-Rice model	168
5.1.3	Sensitivity analysis of the CERES-Rice model	169
5.2	Summary of the results	170
5.2.1	Grain yield	170
5.2.2	Above ground biomass	171
5.2.3	Phenological events	172
5.2.4	Leaf area index	173
5.2.5	Number of grains per square meter, grain number per panicle, test weight and harvest index	174
5.2.6	Sensitivity analysis	175
5.3	Conclusions	177
5.4	Future line of work	178
REFERENCES		I - xxviii
APPENDICES		I - viii

LIST OF TABLES

Table No.	Title	Page No.
3.1	Mechanical composition of soil of the experimental field	86
3.2	Physico-chemical properties of soil of the experimental field	86
3.3	Description of the cultivars grown	88
3.4	Fertilizer doses (kg ha ⁻¹) for seed bed and main field	91
3.5	Control measure of pest and diseases	92
3.6	List of input required by CERES-Rice model	99
3.7	CERES-Rice model input files	102
3.8	CERES-Rice model output files	103
3.9	CERES-Rice model experiment data files	103
3.10	Genetic Coefficients for the CERES Rice model	108
3.11	Genetic coefficients for four different cultivars of aromatic rice at Nawagam (middle Gujarat agroclimatic) condition	109
4.1	Average values of various weather elements (Max. Temp., Min. Temp., Mean Temp., BSSH and Mean V.P.) prevailed and total rainfall occurred during crop growing period under various dates of transplanting in <i>kharif</i> 2007 and 2008	117
4.2	Effect of dates of transplanting on grain yields of various cultivars of rice	119
4.3	Effect of dates of transplanting on straw yield of various cultivars of rice	124
4.4	Effect of dates of transplanting on above ground biomass of various cultivars of rice	127
4.5	Error percent by CERES-Rice simulated grain yield from observed during 2007	132
4.6	Error percent by CERES-Rice simulated grain yield from observed during 2008	133

Table No.	Title	Page No.
4.7	Error percent by CERES-Rice simulated grain yield from observed (pooled of 2007 and 2008)	133
4.8	Test criteria in evaluation of model with respect to grain yield (kg ha ⁻¹)	134
4.9	Error percent by CERES-Rice simulated above ground biomass from observed during 2007	137
4.10	Error percent by CERES-Rice simulated above ground biomass from observed during 2008	138
4.11	Error percent by CERES-Rice simulated above ground biomass from observed (pooled of 2007 and 2008)	138
4.12	Test criteria in evaluation of model with respect to above ground biomass	139
4.13	Error percent by CERES -Rice simulated days to anthesis from observed during 2007	143
4.14	Error percent by CERES -Rice simulated days to anthesis from observed during 2008	144
4.15	Error percent by CERES -Rice simulated days to anthesis from observed in case of pooled data (2007 and 2008)	145
4.16	Mean error percent by CERES-Rice simulated days to anthesis in various genotypes of aromatic rice during 2007, 2008 and pooled data (2007 and 2008)	145
4.17	Test criteria for evaluation of the model with respect to simulation of days to anthesis in rice	146
4.18	Error percent in model simulated days to maturity from their observed in rice during 2007	148
4.19	Error percent in model simulated days to maturity from their observed in rice during 2008	149
4.20	Error percent in model simulated days to maturity from their observed in rice on the basis of pooled data (2007 and 2008)	150
4.21	Mean error percent by CERES -Rice simulated days to maturity in various genotypes of aromatic rice during 2007, 2008 and pooled data (2007 and 2008)	151
4.22	Test criteria in evaluation of model with respect to days to physiological maturity	151
4.23	Error percent by CERES-Rice simulated maximum leaf area index from observed during 2007	153
4.24	Error percent by CERES-Rice simulated maximum leaf area index from observed during 2008	153

Table No.	Title	Page No.
4.25	Error percent by CERES-Rice simulated maximum leaf area index from observed (Pooled of 2007 and 2008)	154
4.26	Test criteria in evaluation of model with respect to maximum leaf area index	154
4.27	Test criteria in evaluation of model with respect to grain numbers per square meter	156
4.28	Test criteria in evaluation of model with respect to grain numbers per panicle	157
4.29	Test criteria in evaluation of model with respect to test weight	158
4.30	Test criteria in evaluation of model with respect to harvest index	159
4.31	Sensitivity of CERES-Rice model to photoperiod (h) for various cultivars of aromatic rice	160*
4.32	Sensitivity of CERES-Rice model to solar radiation ($\text{MJm}^{-2} \text{ day}^{-1}$) for various cultivars of rice	161*
4.33	Sensitivity of CERES-Rice model to maximum air temperature ($^{\circ}\text{C}$) for various cultivars of aromatic rice	162*
4.34	Sensitivity of CERES-Rice model to minimum air temperature ($^{\circ}\text{C}$) for various cultivars of aromatic rice	163*
4.35	Sensitivity of CERES-Rice model to elevated CO_2 concentration for various cultivars of rice	164
4.36	Sensitivity of CERES-Rice model to transplant age (Days) of seedlings for various cultivars of aromatic rice	165*
4.37	Sensitivity of CERES-Rice model to plant population (plant m^{-2}) for various cultivars of aromatic rice	166*

* After page

LIST OF FIGURES

Figure No.	Title	After page
3.1	Weekly weather parameters during the experimental crop year <i>kharif</i> 2007	85
3.2	Weekly weather parameters during the experimental crop year <i>kharif</i> 2008	85
3.3	Experimental lay out	90
3.4	Flow chart of experiment and treatment selection	101
3.5	Flow chart showing initialization growth and various ontogeny parameters	101
3.6 A	Flow chart showing daily simulation of various parameters based on weather data	101
3.6 B	Flow chart showing daily simulation of various parameters based on weather data	101
3.7	Flow chart of various output files	101
3.8	Overview of input and output files used by CERES-Rice model	101
4.1	Temporal variation in temperatures during crop growing period under different dates of transplanting in 2007	112
4.2	Temporal variation in weather parameters during crop growing period under different dates of transplanting in 2007	112
4.3	Temporal variation under temperatures during crop growing period in different dates of transplanting in 2008	113
4.4	Temporal variation in weather parameters during crop growing period under different dates of transplanting in 2008	113
4.5	Temporal variation in ten days total rainfall during crop growing period under different dates of transplanting in 2007 and 2008	116
4.6	Comparison of CERES-Rice model simulated grain yield with that observed during 2007	131
4.7	Comparison of CERES-Rice model simulated grain yield with that observed during 2008	131
4.8	Comparison of CERES-Rice model simulated grain yield with that observed (pooled 2007 and 2008)	131
4.9	Comparison of CERES-Rice model simulated above ground biomass yield with that observed during 2007	135
4.10	Comparison of CERES-Rice model simulated above ground biomass yield with that observed during 2008	135

Figure No	Title	After page
4.11	Comparison of CERES-Rice model simulated above ground biomass with that observed (pooled 2007 and 2008)	135
4.12	Comparison of actual and simulated periodic dry matter under different dates of transplanting during 2007	140
4.13	Comparison of actual and simulated periodic dry matter under different dates of transplanting during 2008	140
4.14	Comparison of actual and simulated periodic dry matter under different dates of transplanting on the basis of pooled data	140
4.15	Comparison of model simulated and observed days to anthesis in various genotypes of rice under different dates of transplanting	142
4.16	Comparison of model simulated and observed maturity days in various genotypes of rice under different dates of transplanting	148
4.17	Comparison of actual and simulated temporal leaf area index under different dates of transplanting in 2007	152
4.18	Comparison of actual and simulated temporal leaf area index under different dates of transplanting in 2008	152
4.19	Comparison of actual and simulated temporal leaf area index under different dates of transplanting on the basis of pooled data	152
4.20	Comparison of observed and simulated grain number per sq. meter of various genotypes of rice under different dates of transplanting	155
4.21	Comparison of observed and simulated number of grains per panicle of various genotypes of rice	157
4.22	Comparison of observed and simulated test weight (g) of various genotypes of rice under different dates of transplanting	158
4.23	Comparison of observed and simulated harvest index in various genotypes of rice under different dates of transplanting	159
4.24	Effect of altered photoperiod on grain yield of various genotypes of rice as compared with base yield	160
4.25	Effects of altered solar radiation on grain yield of various genotypes of rice as compared with base yield	161
4.26	Effects of altered maximum air temperature on grain	162

Figure No.	Title	After page
	yield of various genotypes of rice as compared with base yield	
4.27	Effects of altered minimum air temperature on grain yield of various genotypes of rice as compared with base yield	163
4.28	Effects of elevated carbon dioxide on grain yield of various genotypes of rice as compared with base yield	164
4.29	Effects of direct sowing on grain yield of various genotypes of rice as compared with base yield	164
4.30	Effect of change in transplanting age of seedling on the grain yield of the various genotypes of rice as compared with base yield	165
4.31	Effect of plant population on grain yield of various genotypes of rice as compared with base yield	166

Introduction

I. INTRODUCTION

1.1. Rice

Rice (*Oryza sativa*), one of the three most important food crops in the world, forms the staple diet of 2.7 billion people. It is grown successfully in different parts of the world from 39°S south (Australia) to 50°N latitude (China). It can grow at altitudes ranging from 10 feet below sea level to 10,000 feet above sea level. Rice is a major food crop that is grown in dry land (or upland) conditions on mountain slopes as well as in wetland conditions in Valley bottoms and in terraced fields. It is a subsistence crop for most farmers (Pandey *et al.*, 2006). Rice is the longest continuously grown cereal crop in the world and according to the International Rice Research Institute (IRRI) it is “one of the most important developments in history” (Forssell, 2008). It is grown in all the continents except Antarctica, occupying 150 million hectare (M ha) and producing 573 million tonnes (Mt) paddy with an average productivity of 3.88 tonnes per hectare ($t\ ha^{-1}$). Its cultivation is of immense importance to food security of Asia, where more than 90% of the global rice is produced and consumed (Anon., 2006a). Rice is seen as a political good in many Asian countries due to its big impact on economy, society and political stability. Rice production is highly diversified and there are strong consumer preferences and a low degree of substitutability in both production and consumption (Forssell, 2008). Almost three billion people worldwide are dependent on rice for their calorie intake and farming and milling provides employment to many people in the world. In Asia and the Pacific alone, rice production is employing about 300 million people (Anon., 2006b).

The Food and Agriculture Organization (FAO) of the United Nations had declared 1966 the Year of Rice. Due to the importance of rice, year 2004 was declared the International Year of Rice by the United Nations General Assembly (UNGA) in 2002 with the aim of once again turning the attention of the world on rice as an instrument of food security

and poverty reduction (Anon., 2006b). This is the second time that the United Nations has paid such a special tribute to rice, the only food crop honoured twice. Rice is the single most important employment and income source for the rural poor. Besides being an essential food, rice is also an important factor in enriching culture, lifestyles and ecosystem functions. Rice is a symbol of cultural identity, global unity and life (Toriyama *et al.*, 2005). Rice has a meaning beyond just food supply and employment in Asia, namely it is also seen as a political good due to its massive influence on social, economic and political stability.

The origin of paddy rice cultivation is located somewhere in the South Eastern part of Asia and is said to date back at least 7,000 years. Since that time, the distribution of paddy rice cultivation has been greatly expanded, but even today it is basically confined to monsoon Asia, near its place of origin. This is not the case for other major cereals such as wheat and maize, which have expanded their area of distribution throughout the world. Kawaguchi and Kyuma (1977) consider that this specific distribution pattern of rice is the result of two factors. One is the concentration of rainfall, often more than 1000 mm during the rainy season and the other is the very large expanse of lowlands in monsoon Asia. This indicates that tropical Asia, with only 1/13 of the world's land area, has more than 1/3 of the potentially arable lowlands. Rice is the crop best suited to such lowlands, where water inundates naturally as rainfalls and rivers flood. Thus, a unique combination of climate and landform has helped create the paddy rice system in Asia.

The rice-plant is a type of grass whose grain is what we call rice. The rice takes between 90 to 200 days to mature and there exist about 1, 20,000 different types of rice, both cultivated and wild varieties. In the International rice gene bank at the International Rice Research Institute (IRRI), there are more than 1, 00,000 rice accessions stored (Anon., 2002).

Differences between species are based on characteristics such as biotic factors; productivity, resistance to disease and insects, and so called non-biotic factors, toleration of cold and drought etc. and many other variables (Forssell, 2008). The genus *Oryza* has two cultivated and 22 wild species. Of the two cultivated species, *O. sativa* (2n=24 AA), commonly referred to as Asian rice, is grown worldwide, whereas *O. glaberrima* (2n=24 AA), “African rice,” is cultivated in a limited area in West Africa (Brar, 2005). Rice grown in Asia has two subspecies *Oryza sativa* L. subsp. *indica* which originated in India and *Oryza sativa* L. subsp. *japonica* which has its origin in the eastern part of Asia (Forssell, 2008). Rice can be divided into different groups depending on its characteristics and is usually classified after the shape of the grain and its kernel form. Rice is divided into long-, medium- and short-grain varieties, where long-grain rice is usually longer than 6.2 milli meters (mm) or about three times long of its width. Medium-grain rice is approximately 2.1 to 2.9 times long of it is width. And last, the category short-grain rice is less then twice as long as it is wide. Rice can be divided into different sub-groups such as aromatic rice which includes types of rice with strong tastes such as jasmine and Basmati, which are both long-grain and non-glutinous. Another group is glutinous rice, also called sticky rice, which contains a high degree of starch and of which there are both long- and short grain varieties. Fourteen different varieties of rice are grown in different areas and are also consumed in different parts of the world.

Rice and rice-based products derived from rice grain and rice flour include parboiled rice; quick-cooking rice and ready to eat convenience foods; rice flours; rice starch; cakes and puddings; baked breads and crackers; breakfast cereals and expanded rice products; extrusion-cooked and puffed rice snacks; noodles, paper and pasta; by/weaning foods; fermented foods and beverages; pet foods; and bran products (Juliano,

2005). Rice is processed and used as various kinds of foodstuffs besides direct food use, such as parboiled rice, fermented rice wine, rice noodles, rice crackers, rice cakes, rice snacks, rice flour, and other fermented rice products (Ohtsubo *et al.*, 2005).

Indian economy is mainly based on agriculture. Growth rate for overall GDP of India was 8.5% whereas for agriculture and allied sectors it was 10% (Anon., 2007). India is the largest growing country (8°N to 34°N latitude) of the rice under varying climatic conditions and it accounts for more than 40% of food grain production, providing direct employment to 70% people in rural areas. Being the staple food for more than 65% of the people, our national food security hinges on growth and stability of its production (Anon., 2006a).

1.1.2. Aromatic rice and its characteristic features

Every state in the country has its own quality/specialty rice varieties. Aromatic or scented rice have long been highly regarded in Indian society not only because of their excellent quality but also because they had been considered auspicious (Ahuja *et al.*, 1995). The aromatic rice varieties in the states of West Bengal, Orissa, Chattisgarh, Bihar and North East region are very short, fine grained and highly scented. Each one is highly priced in the locality where they are grown. These varieties are characterised by weak stem, very long growth duration, low grain weight and poor yield. Farmers mainly grow these varieties for their own consumption and ceremonial purposes and they do not have well developed market.

There is another category of aromatic rice varieties, which is long grained with a unique combination of grain, cooking and eating quality. Quality traits of these rice varieties are best expressed when grown in North Western region of the Indian subcontinent. India and Pakistan are the traditional producers and exporters of Basmati rice and in the world

market it fetches three times high price than high quality non Basmati type rice. Due to polygenic nature of inheritance of the several quality characters, it has been difficult to increase the yield potential of Basmati rice varieties while retaining the same quality characteristics.

The word “Basmati” has been designed from two Sanskrit roots: *vas* (meaning aroma) and *mayup* (meaning ingrained or present from the beginning). Thus the word Basmati implies “ingrained aroma”. So it is the aroma that gives Basmati its novel characteristics unmatched by any other rice grain anywhere else in the world. Many scented varieties of rice have been cultivated in the Indian sub-continent from time immemorial but Basmati distinguishes itself from all other aromatic rice due to its unique aromatic characteristics coupled with silky texture of its long grain. There is general notion that any aromatic rice is Basmati, however this is not the case (Mani *et al.*, 1993). No single criterion can distinguish Basmati rice from other rices.

A harmonious combinations of minimum kernel dimensions, intensity of aroma, texture of cooked rice high volume expansion during cooking made up by linear kernel elongation with minimum breadth wise swelling, fluffiness, palatability, easy digestibility and longer self life quality makes a rice to be Basmati in consumers and traders view (Singh *et al.*, 1988). The special characteristics of Basmati rice are (a) a ‘greasy’ look without any abdominal white, (b) an entire rice grain, (c) fully developed and uniform kernel, (d) neither too soft nor too hard when crushed under the teeth, (e) nearly double elongation after cooking, (f) absence of bursting or stickiness and (g) sweetness and special aroma of the cooked rice (Sharma and Nayak, 2005).

1.1.3. Area and production of rice crop

Worldwide production and yield of crops have been increasing since 1960 due to the adoption of modern varieties, the expansion of

agricultural lands and the use of intensification measures (Abelson, 1995; Matson *et al.*, 1997). Yield growth accounted for almost all of the increases in food production in developing countries. Modern varieties accounted for 21% of the growth in yields and about 17% of production growth in the early Green revolution period and accounting for almost 50% of yield growth and 40% of production growth in the late stage for all developing countries. Land expansion accounted for about 20% of the increases in production and the rest came from intensification of input use (Evenson and Gollin, 2003).

Rice production has been increased tremendously from 20.6 Mt in 1950-51 to 93 Mt in 2001 -02 due to increase in area under rice from 30.8 to 44.6 M ha and productivity from 668 to 1804 kg ha⁻¹(Anon., 2003). The Paddy production in Gujarat was 1277 thousand tonnes from 675 thousand hectares in 2003-2004 whereas it was 1197 thousand tonnes from 679 thousand hectares in 2004-2005 i.e., production was decreased by 6.26% over previous year even though area was increased by 0.59% over previous year. The Productivity of rice in Gujarat state is very poor i.e., 1,356 kg ha⁻¹ as against 1,947 kg h⁻¹ a average productivity of the nation. More than 40% rice area is concentrated in very low productivity group followed by nearly 40% area in medium to low productivity group (Anon., 2006c).

The major factor that has contributed to poverty alleviation is the reduced unit cost of production and the downward trend in real prices of food. Low food prices benefited the urban laboring class and the rural landless and marginal farmers who are net buyers of food from the market. As a result, the food entitlement of the poor improved substantially. In future, expansion of area under rice is very unlikely due to tremendous increase in population and urbanization. Therefore, increasing demand has to come from increase in productivity per unit area. For achieving this, one

of the prime requirements and non monetary input is transplanting the suitable cultivars at an appropriate time.

1.1.4. Aromatic rice growing regions

Basmati rices have been traditionally cultivated in northern India, confined mainly to Punjab, Haryana, Western Uttar Pradesh and adjoining districts of Rajasthan. It is said that Basmati grows best and produces best quality grains under warm, humid, valley like conditions. Experience has also shown that when true Basmati varieties are cultivated outside these traditional Basmati areas, the grains do not have the same quality. During vegetative period high humidity (70 to 80%) and a temperature ranges of 25 to 35°C are favourable. From flowering onwards bright and clear sunny day with a temperature range of 25 to 32°C, comparatively cooler night (20 to 25°C), moderate humidity and gentle wind velocity at the time of flowering and maturity are considered necessary for proper grain and aroma development. The area under Basmati rice cultivation in India is 1 M ha and in Pakistan is 0.75 M ha. In India highest area under Basmati rice is in Uttar Pradesh (0.4 M ha) followed by Haryana (0.25 M ha), Uttranchal (0.10 M ha), Punjab (0.10 M ha), Jammu & Kashmir (0.05 M ha) and Rajasthan (0.05 M ha) documented by Sharma and Nayak (2005).

Basmati rice has been in cultivation for generations in North Western India confined mainly to Punjab, Haryana, Western U.P. and adjoining district of Rajasthan. Introduction of high yielding varieties further contributed to the reduction in acreage during the early seventies. However, with the establishment of modern mills in the early eighties and on increase in the export demand, there has been continuous increase in the area under Basmati rice cultivation (Anon., 2004). At present, India produces about 1.2 Mt (rough rice basis) with an average of 1.5 to 1.8 t ha⁻¹ from 0.7 to 0.8 M ha which is 1.6 to 1.9 per cent as compared to the area under non-Basmati rice (Singh and Singh, 2003).

In Gujarat Basmati and non-Basmati type of rice grown in Daskoshi area of Kheda pockets of Anand and Bavala of Ahemadabad district and part of Saurashtra with the productivity ranged from 1500 to 3000 kg ha⁻¹. Both transplanted and drilled types of rice grown in Gujarat. Shukhvel-20, GR-3, GR-4, GR-6, GR-7, GR-11, Jaya, GR-12, TR-22, SLK-51214, Gurjari, Dandi, Mahsuri, GR-103 are Non-Basmati varieties where as GR-101, GR-102, GR-104, Narmada, Krishna kamod, Pankhali are Basmati varieties comes under transplanted types of rice and GR-5, GR-8, TR-28, GR-9, Sathi 34-36 and local varieties of tribal areas are drilled types of rice grown in Gujarat. Total production of Basmati rice in Gujarat is 12093 metric tonnes (mt) from 6483 ha with the productivity of 1865 kg ha⁻¹.

1.1.5. Status of rice production and its requirement by 2030

The rice is a staple food and continuous supply is to be maintained to the consumers. To ensure regular supply of the food grain proper steps are required to be taken in advance. If supply is not maintained uninterrupted than there are chances of a large number of human population drowning in perpetual hunger. About 1 billion households depend on rice cultivation for employment and their main source of livelihood. As the rice consuming population continues to grow, and the land and water resources needed for rice production diminish, we may face a potential crisis. World rice production has been less than rice consumption since 2000. This insufficiency has been addressed by drawing on rice from buffer stock. In this context, advances in science and technology, as well as rice research, are increasingly critical to enhance rice production and sustainable agricultural development. Ensuring an increase in sustainable rice production will require innovation and cooperation within the scientific community, as well as commitment and shared responsibility among all stakeholders (Toriyama *et al.*, 2005).

Paddy rice and wheat could have an equivalent share in global cereals production till 2030. Paddy rice and wheat is estimated to account for 2/3 of the cereals production. Both paddy rice and wheat should be the dominant cereal food in the world before 2030. Per capita cereals production for developed countries, wheat would amount to 1/3 of cereals and paddy rice has a very low proportion, which demonstrates that wheat should be the dominant cereal crop in these countries. Unlike developed countries, paddy rice is expected to be the dominant cereal crop (1/2) and wheat is just 1/2 of paddy rice in developing countries per capita production.

Paddy rice yield would increase by 2030 to 24.7 to 35.5% and reach 5.28 to 5.73 metric tonnes/hectare (mt ha⁻¹). Paddy rice production in developing countries is estimated to grow at annual rate of 9, 476, 885 mt, much higher than developed countries (74, 027 mt yr⁻¹). Till 2030 the production in developing countries is expected to significantly raise 30.9 to 41.8% against the probable increase of 7.6 to 21.0% in developed countries. Yield increase in developing countries (25.6 to 36.9%) may also be higher than developed countries (4.0 to 23.1%). With a projected production of 5.9 to 7.7 mt, Asia is forecasted to be still the major region for paddy rice production in the world. By 2030 Asia's paddy rice yield is estimated to increase 11.7 to 23.4% and reach 4.59 to 5.08 mt ha⁻¹. On the other hand, Europe (79.0 to 139.2 kg ha⁻¹ yr⁻¹), Oceania (69.3 to 106.7 kg ha⁻¹ yr⁻¹) and North & Central America (65.8 to 74.0 kg ha⁻¹ yr⁻¹) are estimated to have higher annual rates in paddy rice yield, and the production in these regions is expected to reach 7.6 to 9.7 mt, 8.8 to 12.4 mt and 7.4 to 8.2 mt respectively by 2030.

Per capita cereals production of the world is estimated to probably increase 4.5% (1.3 to 10.2%) and reach 375.3 kg yr⁻¹ by 2030. Per capita production in developed countries (7.9 to 39.5%) may have a much higher

level than developing countries (0.2 to 7.7%) and is projected to be three times of the later (899.1 kg yr⁻¹ *vs.* 273.8 kg yr⁻¹) till 2030. Oceania (955.2 kg yr⁻¹) and North & Central America (833.6 kg yr⁻¹) may have the greatest per capita cereals production, while per capita production in Caribbean (62.1 kg yr⁻¹) and Africa (122.2 kg yr⁻¹) should be lower by 2030. Asia is forecasted to be the largest region in cereals production but per capita production in this region (233.3 kg yr⁻¹) may still be lower (Zhang, 2007).

India is essentially an agricultural country with over three-fourths of the population living in rural areas and dependent on agriculture related occupations. Pre-Independent India was badly hurt by frequent famines and drought. The eminent economist Amartya Sen owes his major works on hunger to the devastations of the great Bengal famine which had made deep impressions on him when he was still a child. If India today is self sufficient in food, it is in no small measure due to indigenous agricultural research. Of course, India still has a long way to go. The population is increasing; the land area under cultivation is decreasing and excessive use of chemical fertilisers, pesticides and insecticides are adversely affecting the environment. Far more needs to be produced than now, and produced in a much safer way. These are enough challenges to keep our agricultural research establishment busy. Modern day rice variety have yield potentials much greater than their traditional predecessors, a characteristics that has greatly increased rice production worldwide (Khush, 1987).

Rice production increased with time, this might be due to technological advances and more efficient use of inputs coupled with increased area under cultivation. Still there are few downfalls which clearly states that prevailing weather has significant effect on yield of rice. Rice production may change as a result of global warming through the CO₂ increase, temperature rise and change in precipitation. Thus, policymakers require reliable projections of the regional impacts on the production in

order to consider mitigation and adaptation techniques. Projections of regional climate change and impact on rice production are important in relation to food security for these areas, as stated by the Intergovernmental Panel on Climate Change (IPCC) in its Third Assessment Report (Anon., 2001).

1.1.6. Role of aromatic rice in the export earnings

India is one of the important countries in the world in export of rice. India's exports are expected to go up further during current financial year. Hence, Indian rice exports are set to reach second place in the world markets after Thailand edging out Vietnam in the process as per the report of the Food and Agricultural Organisation. Basmati export market is a lucrative area. Though India and Pakistan enjoy to have the maximum shares in this market, competitors from others countries are already coming up. Basmati varieties have special characteristics that cannot be found anywhere else in the world. Rice export from India constitutes the major share of Basmati rice. Nearly two-third of Basmati rice produced in India is exported. Basmati rice is the leading aromatic fine quality rice of the world trade and it fetches good export price in the international markets. Infact, Basmati rice is a gift from "Mother Nature" to the Indian sub-continent and grows in the Indo-Gangatic plains only. Basmati rice being novel product is characterized by its unique grain size, aroma and cooking qualities. Being high value product, it has got good export demand. Hence, the export has been very high and exports have been steadily growing. During the year 2000-01, Basmati rice export touched an all time high record figure of 8.52 lakh mt (provisional) showing on increase of 62.9% over 1996-97.

The percentage share of export value of Basmati rice in the food grains export earnings was 76.10 per cent during 1993-94. About 60-70 per cent of the total Basmati production in the country exported every year to

the international market mainly Saudi-Arabia, U.A.E, Kuwait, Oman, Russia, U.K and U.S.A. During 1997-98, India exported around 581791.0 metric tones of Basmati rice (Anon., 2004). There is vast scope for further expansion of Basmati rice export, provided we could supply to farmers dwarf high yielding Basmati varieties along with appropriate production technologies. Hence, to fill this gap between demand and supply, the present investigation will be carried out for achieving this by selecting suitable aromatic cultivar and appropriate time of transplanting.

1.1.7. Future prospects of aromatic rice

For centuries Basmati rice has been the food of choice for rich and enlightened people. Awareness about the unique cooking and eating qualities of Basmati rice is increasing. Every year the domestic and the international demands are on the increase. In India Basmati cultivation is spreading to neighboring districts of Basmati growing states. Modern rice mills with complete automation have further improved the physical quality of Basmati rice. Now, it is possible to separate well developed, high density kernel of uniform size and colour with desired degree of milling. Scientific packing and transportation make it possible to deliver the best product without any deterioration in quality or colour anywhere in the world. Since present day varieties require less input, there is a wave to grow these varieties organically. Basmati rice grown organically has tremendous potential in domestic and international market. Unique climatic conditions available in North West India for growing best quality Basmati rice are unparallel in the world. If high yielding, disease and pest resistant varieties of identical grain and cooking quality are made available, the area under Basmati rice will defiantly increase.

Preference for quality rice has expanded from Southeast Asia to Europe, Africa and United States of America. Over the past few years, there has been a remarkable increase in India's foreign exchange earning

from export of Basmati rice. India has made a definite dent in the global rice trade and, in the coming years it will get a leading slot in the international rice trade.

1.2. Crop growth simulation models

Crop growth simulation models are useful tools for considering the complex interactions between a range of factors that affect crop performance, including weather, soil properties and management. Where pests and diseases are controlled, water and nitrogen fertiliser management are the main factors influencing yield for a given environment. The CERES-Rice models simulate crop growth, development and yield taking into account the effects of weather, genetics and soil water, carbon and nitrogen, planting, irrigation and nitrogen fertilizer management. The rice models can also be run in sequence under the DSSAT framework. Therefore DSSAT/CERES-Rice offers the ability to evaluate options for increasing yield and water and nitrogen use efficiency. However the CERES models do not simulate interactions with shallow ground waters, and salinity dynamics and effects on crop performance.

1.2.1. Origins and genesis of a crop growth simulation model

Crop simulation model approach was started near about 50 years ago, in early 1960s when early simple crop models were developed for estimation of transpiration and photosynthesis. The first step towards crop modelling was the development of simple models to estimate light interception and photosynthesis (Loomis and williams, 1963; De wit, 1965 and Duncan *et al.*, 1967). The belief that a crop model could be developed into relatively simple user-oriented package came from the success of a model developed (Ritchie, 1972) to predict evaporation from plants and soils with incomplete cover. DSSAT v.3.5 has been developed through collaboration between scientists at the University of Florida, the University of Georgia, University of Guelph, University of Hawaii, the International

Center for Soil Fertility and Agricultural Development, Iowa State University and other scientists associated with the International Consortium for Agricultural Systems Applications (ICASA).

1.2.2. Brief description of CERES-Rice model

The CERES models simulate crop growth, development and yield taking into account the effects of weather, management, genetics, soil water, carbon and nitrogen. Since the focus of this research is on performance and applications of these models, only the main features of official versions of CERES-Rice model components and processes are described here.

1.2.2.1. Phenology

The phenology components of CERES-Rice and CERES-Wheat have been described by Ritchie and Ne Smith (1991), Singh (1994) and Ritchie *et al.* (1998). The models describe the progress through the crop life cycle using degree day accumulation (heat sum). The duration of growth stages in response to temperature and photoperiod varies between species and cultivars and genetic coefficients are used as model inputs to describe these differences (Hunt and Boote, 1994; Singh *et al.*, 2002). In wheat, the duration from emergence to terminal spikelet formation is influenced by the vernalization (chilling) requirement and photoperiod. In rice, a developmental phase (juvenile stage) occurs when the crop is not sensitive to photoperiod. After this stage sensitivity to both photoperiod and temperature determine the time to panicle initiation. The phenology component also simulates the effect of water or nitrogen (N) deficit on the rate of life cycle progress (Singh *et al.*, 1999). These effects may vary with life cycle phase; for example, water deficit may slow the onset of reproductive growth but accelerate reproductive growth after the beginning of grain filling.

1.2.2.2. Growth

The models predict daily photosynthesis using the radiation-use efficiency approach as a function of daily irradiance for a full canopy, which is then multiplied by factors ranging from 0 to 1 for light interception, temperature, leaf N status and water deficit. There are additional adjustments for CO₂ concentration, specific leaf weight, row spacing and cultivar (Ritchie *et al.*, 1998). Growth of new tissues depends on daily available carbohydrate and partitioning to different tissues as a function of phenological stage which is modified by water deficit and N deficiency stress indices. Leaf area expansion depends on leaf appearance rate, photosynthesis and specific leaf area. Leaf area expansion is quite sensitive to temperature, water deficit and N stress. During seed fill, N is mobilized from vegetative tissues. As a result, vegetative tissue N concentration declines and this in turn lowers photosynthesis and causes leaf senescence to increase. Protein and carbohydrate mobilized from vegetative tissue contribute to seed growth while photosynthesis declines (Godwin and Singh, 1998). Cultivar differences in yield components, tillering and temperature tolerance are captured by the model using a suite of cultivar specific coefficients.

1.2.2.3. Water balance

The soil water balance model initially developed for CERES-Wheat is used in all of the DSSAT v.3.5 crop models (Ritchie, 1998). This one-dimensional model computes the daily changes in soil water content by soil layer due to infiltration of rainfall and irrigation, vertical drainage, unsaturated flow, soil evaporation, plant transpiration and root water uptake. The soil has parameters that describe its surface condition and layer-by layer soil water holding and conductivity characteristics. The model uses an overflow or “cascading bucket” approach for computing soil water drainage when a layer’s water content is above the drained upper

limit. This has been misleadingly referred to as a “tipping bucket” approach in the past (a tipping bucket completely empties once the “fill” point is reached). Drainage of water through the profile is first calculated based on an overall soil drainage parameter assumed to be constant with depth. The amount of water passing through any layer is then compared with the saturated hydraulic conductivity of that layer. If the saturated hydraulic conductivity of a layer is less than the computed vertical drainage, actual drainage is limited to the conductivity value and water accumulates above the layer. This feature allows the model to simulate poorly drained soils and perched water tables.

CERES-Rice can also simulate the effect of bund height. Floodwater depth, runoff (when floodwater depth exceeds bund height) and evaporation from floodwater are simulated. The model also simulates the effect of puddling on percolation rate and bulk density, temporal changes in these properties and the reversion to a non puddle state. The components of the model to describe puddling effects are rudimentary and would require further work to determine how well they would work in coarse textured soils such as those of North West India.

1.2.2.4. Soil organic mater and N dynamics

The DSSAT v.3.5 model has options to simulate the soil organic matter (SOM) pools and dynamics (Godwin and Jones, 1991; Godwin and Singh, 1998) which has a variable C:N ratio and can mineralize or immobilize nutrients. The SOM decomposition rate and residue flows also vary with soil texture. The N module of CERES-Rice simulates hydrolysis of urea, nitrification, ammonia volatilization, nitrate leaching, denitrification, algal activity and floodwater pH changes, plant N uptake and partitioning under continuously flooded, intermittently flooded and non-ponded conditions (Singh, 1994). The floodwater N chemistry component of the model (Godwin *et al.*, 1990; Godwin and Singh, 1991,

1998) uses an hourly time step to calculate rapid N transformations and to update soil-floodwater-atmosphere equilibria. CERES-Rice, however, does not simulate ammonium leaching, which can be important on coarse textured soils (Katyal *et al.*, 1985).

1.2.3. Applications of CERES-Rice model

Mathews and Stephens (2002) categorized the main applications or needs of models into 3 categories: as tools in research, in decision support and in education and training. Examples of research applications included identification of desired crop genotype characteristics, investigation of management options, cropping or farming system analysis, investigations of impact of climate change on crop productivity and prediction of greenhouse gas production. Models can be used to assist both tactical decision making (such as irrigation scheduling, fertiliser and pest management), or in strategic decision making, such as planning for climate change or to avoid salinisation, yield forecasting and planning for national food requirements. Models can also be useful in teaching crop and soil processes and crop system behaviour in response to weather, management and site conditions.

The major applications of the CERES-Rice models are yield forecasting, yield gap and yield trend analysis, evaluating agronomic management strategies, evaluation of cropping options in new locations, impacts of climate change on yields, prediction of greenhouse gas emissions, pest and disease management and in forming government planning. However, the impact of the application of the models on decision making by farmers and their advisors and policy makers is generally less clear.

Usefulness of models is enhanced if they can be operationalized and harnessed directly or indirectly for farmer's benefit. In production-oriented agriculture, optimum sowing or transplanting time and suitable cultivars

on local area basis are vital aspects that not only determine farm economy and profitability but also intimately associated with sustainable crop productivity.

In Gujarat state, particularly for middle Gujarat agro-climatic zone-III, crop simulation modelling of groundnut (Singh *et al.*, 1994), maize (*rabi*) (Reddy, 1992), *summer* pearl millet (Maniyar, 1993), mungbean (*summer*) (Jadhav, 1999) mustard (Patel, 1994), *summer* pearl millet (Rao, 1995) and wheat (Akula, 2003 and Patel, 2005) have been attempted but simulation modelling of aromatic rice using CERES-Rice model has not been carried out and its performance has not been assessed. Hence, to fill this gap of research, the present investigation has been carried out during the *kharif* seasons of 2007 and 2008 at Main Rice Research station (MRRS), Nawagam, Anand Agricultural University, Anand with the following objectives.

1. To calibrate genetic coefficients of various genotypes (cv. Pankhali, Narmada, GR-104 and Pusa Basmati-1) of aromatic rice for CERES-Rice model (v.3.5).
2. To study the weather based simulation of phenology, growth and yield of various cultivars of aromatic rice.
3. To select the suitable aromatic cultivar for middle Gujarat Agroclimatic region.
4. To determine and validate the optimum transplanting time for various cultivars of aromatic rice under middle Gujarat Agroclimatic region.
5. To carry out the sensitivity analyses of various growth and yield attributing characters.

Review of Literature

II. REVIEW OF LITERATURE

Agrometeorological research in agricultural research institutes in India had its beginning in the earlier years of the 20th century with research efforts on evaporation, soil temperature, soil moisture and soil gases at the then Imperial Agricultural Research Institute at Pusa, predecessor of the present Indian Agricultural Research Institute (IARI) at New Delhi. The activities in this discipline enriched the literature pertaining to the crop weather relationship. This chapter contains the available literature published on the research work related to the problem chosen by the author. Though the review of pertinent literature has been mainly confined to rice crop, relevant research work on some other crops has also been reviewed and relevant information included wherever necessary. The literature reviewed is cited under the following broad headings for convenience.

- 2.1. Effect of weather on growth and yield of rice
- 2.2. Effect of weather on phenology of rice
- 2.3. Effect of date of transplanting or sowing on growth and yield of rice
- 2.4. Crop growth models
- 2.5. Crop growth simulation models
- 2.6. Application of crop growth simulation models
- 2.7. Calibration of crop simulation models
- 2.8. Evaluation of crop growth simulation modelling
- 2.9. Sensitivity study of the simulation models

2.1. Effect of weather on growth and yield of rice

Weather and climate are the integral parts of the agricultural production system that is reflected in the dependence of the country's economy and food grain output on monsoon activity year after year. Weather is an important component not only for crop production but also for horticultural crops, live stock, fisheries, forestry and other areas such

as transport, storage and marketing of agricultural products (Sastry, 2001).

Crop growth and development are primarily governed by environmental conditions of soil and weather. The success or failure of farming and qualitative and quantitative improvement in crop production is intimately related to the prevailing weather conditions. Vagaries of weather phenomena also affect agriculture by interfering with routine agricultural operations and plant protection measures. Further influence of weather on crop growth and yield depends on crop growth stage. Weather assumes significance in nearly every phase of agricultural activity from preparatory tillage to harvesting and storage. Weather affects selection of crop varieties, time of sowing, transplanting, scheduling of irrigation, timing of fertilizer application, using of pesticides etc (Anon., 2006a). The extent of weather influence on crop yield depends not only on the magnitude of weather variables but also on the distribution pattern of weather over the crop season (Chauhan, 2007).

Rice is grown successfully in different parts of the world from 39°S south (Australia) to 50°N latitude (China). In India, it extends from 8°N to 34°N latitude under varying climatic conditions. The optimum climatic requirements for its normal growth include 20 to 35°C temperature through out the crop duration, clear sky during the day for better interception of solar radiation and high photosynthetic activity, low night temperature for reduced maintenance respiration and equitable distribution of rainfall. The optimum climatic conditions are met during winter season (*rabi*) all over the traditional rice belt in general and eastern India in particular , and during rainy (*kharif*) in north west India, resulting in higher yields (Anon., 2006b). Rice and wheat are the two most important cereals in the Indo-Gangetic Plains (IGP) and are responsible for the food security of the region. To understand the productivity trends

in the transects of the IGP: (i) the climatic potential yield of rice and wheat were studied by Pathak *et al.* (2003). Results showed that the potential yields of rice and wheat in the IGP ranged from 7.7 to 10.7 and 5.2 to 7.9 tonnes/hectare ($t\ ha^{-1}$), respectively. The upper transects 2 (Punjab, Haryana and Pakistan) of the IGP are more productive and yield decreases by 27% for rice and by 32% for wheat from transect 2 to transect 5 (Uttar Pradesh, Bihar, Nepal, West Bengal and Bangladesh). The decrease in radiation and increase in minimum temperature were the reasons for the yield decline. The potential yield trend of wheat however, appeared to be stable. On-farm yields of rice also showed a negative trend but for wheat the trend was mostly positive. Hundal and Kaur (1996) also observed that increasing temperature and decreasing radiation levels were the reasons for the decline in simulated potential yield of rice and wheat at Ludhiana.

Das *et al.* (1971) evolved formulae for forecasting the yield of autumn paddy in Mysore State using meteorological factors by means of regression analysis. They found that restricted rainy days from July to 15 September and frequent droughts and floods during August and September were the principal factors having significant effects on yields in coastal Mysore. The corresponding factor for interior North Mysore was drought during July-September. In interior South Mysore, June and September rainfall have a significant effect on yield. The formulae agreed well with reported yields for 1965-1968.

Ishizuka *et al.* (1973) conducted research in Japan on the effects of cold weather on the rice plant and countermeasures which could be taken to avoid or reduce the severity of cold damage in Taiwan. They stressed the importance of continuing research into rice production in cool climates even during periods when climatic conditions were more favourable. Bhargava *et al.* (1974) studied the recurrence of rainfall

deficiency in relation to rice crop at Raipur. They reported that, rainfall during July, September and the total rainfall during the crop season in the district was highly correlated with yield of paddy.

Van (1974) studied the effects of climate on rice yields in Malaysia during both the off-season and main-season rice crop. The off-season crop yielded better than the main-season crop but no significant differences were detected. He found that the performance of the rice crop was affected by the number of rainy days particularly during the growth phase between floral initiation and ripening.

Huda *et al.* (1975) studied the contribution of climatic variables in predicting rice yield in Pantnagar. They used a second degree polynomial multiple regression equation. They reported that average weekly total rainfall is beneficial during the nursery period and detrimental during vegetative and ripening phases. Above-average maximum daily temperature was beneficial during the 1st 3 weeks of establishment and slightly detrimental during the next 2 weeks, then had an increasing adverse effect which was greatest at maximum tillering and ear initiation and was still severe during flowering; a decrease of 1°C was beneficial. A 1°C increase in average minimum daily temperature was beneficial during establishment and had a progressively increasing adverse effect throughout flowering and ripening. Grain yields were decreased by increased maximum and minimum relative humidity and increased at low relative humidity.

Sunlight was more critical for grain yield during the reproductive than the ripening phase (IRRI, 1975). Similarly, Robertson (1975) at WMO discussed the methods of forecasting paddy yield and distribution of rice cultivation throughout the world with particular reference to climate and weather. Growth and development of the rice plant were detailed with its environmental requirements and problems of irrigation discussed in

detail. Numerous data were presented on the climatic zonation of rice in monsoon regions and the bioclimatic conditions in rice-producing areas.

Keulen (1976) developed a model for calculating the potential grain production of rice from temperature and solar radiation in Indonesia. Despite the difficulties of achieving potential production, there was general agreement between the actual and estimated potential values of grain production of Surinam and Indonesian rice crops for which experimental and climatological data were available. He suggested that the model could be applied for screening yield potential in breeding programmes.

Munakata (1976) studied the joint effects of radiation and temperature on rice growth and yield by the non-linear multiple regression models, using data obtained annually in major rice-producing areas in Japan. He stated that the effect was not linear and varied with growth stage of the crop. He found that the number of spikelets/m² was strongly influenced by temperature at (a) 45 and (b) 20 days before heading, and by solar radiation at (c) 40 days prior to heading, when the effect of temperature + radiation on the number of spikelets/m² was greatest. The grain yield/number of spikelets quotient (ripening grade) was governed by the climatic factors at (b) and at (e) 20 days after heading. Solar radiation had a positive effect throughout the reproductive stage. Low temperature at (b) and at (f) 10 days after heading and high temperature at heading proved negative to ripening grade, with normal solar radiation. Multiple regression equations were fitted to study relation of temperature and spikelet numbers, grain yield and climatic factors; grain yield and light along with temperature.

Yoshida and Parao (1976) studied climatic influence on yield and yield components of low land rice in the tropics at Philippines. They reported that the grain yields were highly correlated positively with

average daily solar radiation and negatively with average daily mean temperature during the reproductive stage, i.e., the 25 day period before flowering. Controlled-environment and field studies demonstrated that variations in temperature and solar radiation within ranges commonly encountered during the vegetative stage did not have any overall effects on yield and yield components. Relatively low temperature and high solar radiation during the reproductive stage had remarkable effects on increasing spikelet number and hence grain yield. Solar radiation during the ripening period influenced grain filling. Yield and yield components data collected from various locations in the tropics indicated that the probability of weather conditions before or after flowering having a greater effect on yield was location or season specific. A 3 year average annual production from 4 crops /year was 23.7 t ha⁻¹. Hence, total dry matter production was estimated at about 35 t ha⁻¹ yr⁻¹. They concluded that on a yield/crop basis, the tropical environment may not necessarily be more productive than the temperate region, but it has a greater potential in terms of annual production.

Rainfall distribution was a major factor affecting the performance of rainfed rice crop (IRRI, 1977). Strommen (1977) outlined a modelling approach which gives a qualitative estimate of potential crop yields using agrometeorological data for an early warning system for food crops including rice in India, Haiti, Pakistan, Bangladesh, USSR and China. The merit of this approach was that it utilized an existing data system; it could be implemented with limited resources and in a short time span; and a large and detailed historical yield database was not required. The model was especially recommended for maize, rice, soybeans and wheat.

Rao (1978) fitted a regression equation for yield and significant weather parameters to study the effects of weather on productivity of rice in Kenya and found positive effects of mean temperature and a negative

effect of radiation on yield. Due to altitude (1159 m) the effect of weather conditions was significantly different from other places around the equator and at near sea level.

Chaudhary and Sodhi (1979) studied the effect of weather factors on growth of rice cv. Taichung (Native) 1 sown at 14 days intervals from 15 May to 30 April and transplanted after 14 to 21 days at Kharagpur. They reported that the growth duration varied with air temperature and increased in proportion to the length of time the plants experienced low temperature during vegetative growth and flowering. Temperature accounted for 86% of the variation in growth duration. Winter sown plants produced the largest number of tillers and highest straw yield. Minimum spikelet sterility (12 to 18%) was found in November sown plants which experienced temperature of 27 to 28°C during flowering. Sterility increased when plants were exposed to higher or lower temperature during flowering. Highest yields were in plants sown from 13 November to 11 December.

Jain *et al.* (1980) studied the effect of climatic variables on rice yield and its forecast in Raipur district, M.P. for the period from 1947 to 1971. The effect of total weekly rainfall was found beneficial throughout the crop season. The reliable forecast was possible after about two months of sowing, assuming that weather would be remaining normal thereafter.

Ramdoss and Subramaniam (1980) studied the influence of weather parameters during the last 45 days of crop growth on rice yield at Coimbatore. They reported that the maximum temperature and number of sunshine hours had a positive effect on paddy yield and a negative effect on straw yield.

Agrawal *et al.* (1983) studied the joint effects of climatic variables on rice yield at different stages of crop growth in Raipur district. Beneficial effect was observed on yield for above average maximum temperature

with rise in humidity during active vegetative phase while detrimental effect was observed in other phases of crop growth. The rise in humidity has small beneficial effect in general throughout the crop season. The effect increased with increase in temperature. Rise in temperature associated with high rainfall had beneficial effect during growth phase of the crop.

Lomas and Herrera (1985) studied weather and rice yield relationships in tropical Costa Rica. They reported that the rice yield were most variable due to low rainfall. They concluded that rainfall during August when rice was in the reproductive stage could be used to assess rice yields.

Chatterjee and Mandal (1988) reported that high rainfall, low radiation and high pest incidence were detrimental to high crop production in West Bengal, Orissa, Bihar and East Uttar Pradesh. They reported that under rainfed conditions in the *kharif* season high rainfall, low radiation and high pest incidence were detrimental to high crop production. They stressed that efforts were needed to compensate for low production in the *kharif* season by increasing the productivity of *rabi* (winter season) crops, under both rainfed and irrigated conditions.

Viswambharan *et al.* (1989) delineated climatic constraints of high-yielding photo-insensitive winter rice in Kerala. They reported that excessive wind velocity during flowering and maturation, low solar radiation and the occurrence of rainy days during maturation phase produced high spikelet sterility and low yields.

Shi and Shen (1990) studied the effect of high humidity and low temperature on spikelet fertility in 12 varieties of *indica* rice in China. They have reported that spikelet fertility was reduced with increasing RH and decreasing temperature. RH was the most significant meteorological

factor affecting spikelet fertility followed by mean temperature at 3 days after heading. Spikelet fertility also varied with variety.

Reddy and Reddy (1992) used correlation co-efficients for establishing crop weather relationships in rice at Rajendranagar. They correlated grain yield with number of rainy days, sunshine hours, humidity and maximum temperatures during the pre- and post-flowering stages. They reported that the grain yield was negatively correlated with number of rainy days and humidity during the vegetative stage and with maximum temperatures and humidity during the reproductive stage, but was positively correlated with sunshine hours during the pre- and post-flowering stages.

Jacobs and Pearson (1994) used a mathematical model based on the daily cycle of temperature on development of rice in Australia. They reported that the daily impact of cold varies with the phenology of the crop and total or cumulative impact depends on the summation of thermal time below a critical minimum temperature for cold damage. They noted that owing to exposure to suboptimal ($<20^{\circ}\text{C}$) temperatures, cold damage took the form of reduced yield, abnormal spikelet development and reduced spikelet fertility.

Yang and Yang (1994) studied effect of solar radiation and air temperature on rice cv. Tainung 67 yield in Taiwan at 5 different levels of water deficit. They found that rice yield increased with increasing total solar radiation and heat sums, decreased with increased water stress, but was not significantly affected by total sunshine hours or rainfall.

Samui (1995) studied the influence of variations in rainfall on rice yield in Gangetic West Bengal with 10-year moving averages. He found marked variation between years in rainfall and rice yield. He reported that yield increase were due to improved management practices and not due to rainfall.

Singh *et al.* (1996) studied the influence of agroclimatic elements on the yield of rice at Raipur. The crop period was divided into different phenological phases of rice. The bright sunshine hours, maximum and minimum temperatures were negatively correlated with yield in all the phases. The yield variation explained by afternoon relative humidity was maximum, followed by those of rainfall, maximum temperature, bright sunshine hours, minimum temperature and morning relative humidity.

Samui *et al.* (1998) used curvilinear technique to investigate the relationship between weather and rice yield at Pattambi. They reported that yield fluctuated with change in average daily temperature, bright sunshine hours and total rainfall during different growth stages of the crop. The yield increased as the average daily temperature increased from 21.5°C; yield decreased as the average daily temperature increased from 29.1°C; yield slowly decreased as the total bright sunshine hours during planting to harvesting increased from 300 to 450 h (beyond 450 h the fall was rapid); and yield decreased with increase in total rainfall during planting to maturity from 900 to 1100 mm.

Samui (1999) used curvilinear technique to examine the influence of meteorological parameters on the yield of rice at some stations in India. He reported that highest yield was obtained when average rainfall ranged between 100 and 115 cm. Maximum and minimum temperature ranges of 29 to 32°C and 23 to 25°C, respectively, gave optimum yield.

Kaladevi *et al.* (1999) evaluated the effect of agrometeorological factors (maximum and minimum temperature, relative humidity, solar radiation, wind speed, evaporation and total rainfall) on the yield of *rabi* rice in Tamil Nadu. They reported that increased lower minimum temperatures resulted in higher dry matter production (dry matter produced for a degree difference between maximum and minimum temperature).

Gupta *et al.* (2000) correlated the effect of rainfall, number of rainy days and length of rainy season with productivity of rice in Jabalpur. They reported that rice yields were significantly correlated with quantum of rainfall, length of rainy season and number of rainy days. They concluded that for obtaining higher productivity of rainfed rice either surplus rain water be efficiently managed to overcome moisture stress during reproductive phase or to minimise the risk of moisture stress during grain filling, short duration varieties be selected which were better in water use efficiency and drought tolerant.

Sarangi *et al.* (2001) developed a regression model to forecast transplanted summer rice grain yield using growth and environmental parameters in Orisa. They reported that the grain yield was positively and significantly correlated with growth characters. The grain yield was poorly correlated with temperature sum from flowering to ripening but strongly correlated with sum of bright sunshine hours during entire growth period. They concluded that on the basis of data available till flowering, this regression model could predict the yields of rice grain with 90 to 95% confidence.

Sarmah and Handique (2001) utilised multiple regression approach for preharvest forecasting of winter rice productivity for Jorhat district of Assam. They reported that weekly total rainfall, average weekly maximum temperature, average weekly bright sunshine hours, average weekly morning and evening relative humidity exhibited positive effect on rice yield. They also reported that the best time for rice yield forecasting was in the 43rd standard meteorological week, i.e., 4th week of October.

Jaybhaye *et al.* (2003) studied the relationship of monsoon rainfall with yield of rice crop at Igatpuri. Rice yields showed significant correlations with quantum of monsoon rainfall ($r = 0.48$) and monsoon

rainy days ($r = 0.80$). They reported that precipitation received during critical anthesis and reproductive stage was related with yield.

Nigam and Mishra (2003) studied the correlation between weather factors and rice grain yield in the tarai region of Pantnagar. They reported that effect of weather variables vary according to the time of transplanting. Under early transplanting conditions, the number of sunshine hours was significantly correlated with rice yield. Minimum temperature, maximum relative humidity, minimum relative humidity and rainfall were negatively correlated with yield, whereas the number of rainy days, wind velocity and evaporation were positively correlated with yield. Under timely transplanting conditions, the number of sunshine hours and maximum temperature showed a significant correlation with yield. Yield was negatively correlated with minimum temperature, maximum relative humidity, minimum relative humidity and rainfall, but was positively correlated with the number of rainy days, wind velocity and evaporation. Under late transplanting conditions, only the number of sunshine hours was significantly correlated with yield.

Kumar and Sharma (2005) parameterized and validated CERES-Rice model using experimental results under mid-hill conditions of the North Western Himalayas. They have derived the cultivar specific genotypic coefficients for four different cultivars during calibration. Validation based on several independent sets of yield data, including different locations, years, nitrogen and irrigation water treatments showed good agreement ($R^2=0.7785$) between observed and simulated grain yield. The model predicted phenology of cultivars reasonably well. The model, however, fails to simulate single grain weight. Significant association between simulated and observed grain yield were supported by tests of

significance for intercept and slope of the regression line ($R^2 = 0.7289$). Likewise harvest index was also simulated fairly well by the model.

Choudhury *et al.* (2007) run the CERES-Rice, a dynamic crop simulation model incorporated in DSSAT v.3.5 to simulate the rice yield at Raipur, for the period of 30 years. They reported that the potential productivity of rice ranged from 81.97 to 105.50 q ha⁻¹ whereas; in rainfed condition the range was 33.67 to 89.49 q ha⁻¹.

Sarkar and Kar (2008) reported that the weather variability affects the production of most cropping systems, and rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) rotation is not an exception. Integrating weather forecasts with soil fertility management options is one way to combat the production decrease by anticipating weather variability along with sustaining the soil environment. They used Sequence analysis of DSSAT v.3.5 to select the best combination of crop residue and N application rate for sustainable production of rice-wheat rotation under generated weather. They calibrated and validated CERES-Rice and CERES-Wheat of DSSAT v.3.5 for rice and wheat crops. Weather generator SIMMETEO was used to generate the weather variables of 30 future years. The variables generated by SIMMETEO, which closely matched with actual weather variables, were used for yield prediction by the sequence analysis program driver. The regression analysis showed a strong relationship between generated rainfall values and predicted yield.

2.2. Effect of weather on phenology of rice

Weather is the instantaneous state of atmospheric condition, which is manifested through different parameters like temperature, sunshine hours, relative humidity, rainfall etc. These parameters alone or in combination with one another have a significant bearing on the proper functioning of biological systems. Just like human beings and animals, plants also respond to variation in weather conditions. Crop phenology is

the most important means to study the impact of weather on crop plants. It is the study of timing of recurring natural phenomena such as flowering or senescence of a crop (Munn, 1970). Information of crop phenology is essential for evaluating crop productivity and crop management.

Ghosh *et al.* (1973) studied the effects of weather factors on yield attributes of rice at CRRI, Cuttack using regression technique. They reported that high maximum temperature (29 to 31.5°C) and high total sunshine hours 3 weeks after flowering favoured panicle number and grain weight in the mid season cultivar T-141. They also reported that the absence of rainy days during the ripening phase was not beneficial to grain weight.

Dua and Garrity (1988) tested different models for predicting rice flowering using mean temperature and photoperiod in Phillipines. Data from 43 experiments conducted at 23 irrigated sites in Asia, Africa and South America (latitudes 0°9'S to 37°16'N) were evaluated for relationships between mean temperature, photoperiod and flowering date. Cultivars IR 9729-67-3 (very early), IR 36 and BG35-2 (early) and Taichung Sen Yu 285 (medium) were tested for best fit to generalized thermal or photoperiod models. A simple model using accumulated thermal units accurately estimated the rate of progress to flowering in IR 36. Best fit models included a quadratic photoperiod term that accounted for day length effects. Models for the other cultivars also gave similar performances.

Chakravarty (1990) studied the crop-weather interactions in cereal and pulse crops at IARI, New Delhi. He analysed results of field experiments carried out at various locations in India to understand quantitatively the crop-weather interactions in cereals (rice, pearl millet, sorghum, maize, wheat and barley), legumes (groundnuts, mung beans

and gram) and raya. He reported that PAR interception and utilization by the crop, distribution of rainfall and phenological stage at which it occurs and accumulated heat sums had a linear relationship in cereal crops including rice.

Murai *et al.* (1991) studied relation between cool temperature damage at booting stage and water depth in four dwarf lines of rice in Japan. They reported that cool temperature was prime cause of spikelet sterility. The reduction in spikelet fertility was observed from 31.9 to 58.3% in different lines. Sterility of variety D-47 was not reduced owing to its high sensitivity to cool temperature.

Summerfield *et al.* (1992) studied photothermal responses of flowering in rice in UK. They assumed linear relationship between the rate of progress towards panicle emergence and mean temperature. They recorded the time from sowing to panicle emergence in 16 diverse rice cultivars in 13 different controlled environments comprising constant and diurnally alternating temperatures between 16 and 32°C and photoperiods between 10.5 and 15.0 h day⁻¹. In 11.5 h days and at suboptimal temperatures, relations between the rate of progress towards panicle emergence and mean temperature were linear in all cultivars, and amongst these the base temperature at that photoperiod varied between 6.6 and 11.9°C. In most cases progress was most rapid at 24 to 26°C. They concluded that both temperature and photoperiod had considerable effect on panicle emergence. Differences among cultivars in relative sensitivity of rate of progress towards panicle emergence to both temperature and to photoperiod were considerable; *japonica* cultivars tended to be more sensitive to temperature and less sensitive to photoperiod than *indica* cultivars.

Hoa and Singh (1993) developed regression model to forecast rice yield based on weather parameters at Pantnagar. They reported that the

effect of maximum temperature, minimum temperature and relative humidity was beneficial at the end of the seedling stage. During the vegetative growth stage, relative humidity and total rainfall were found beneficial, while increase in minimum temperature was found harmful. The forecasting model using weather data upto 13th week (the third week of August) was appropriate for forecasting rice yield as it explained 85 % variation in yield.

Godwin *et al.* (1994) documented that night temperatures <18°C immediately preceding flowering in rice crops can adversely affect floret fertility and, hence, yield. They have suggested that sterility induced by low temperature is also influenced by floodwater depth and nitrogen (N) rate.

Collinson *et al.* (1995) studied the relative importance of air and floodwater temperatures on the development of rice cv. IR 36 in both a growth cabinet and a glasshouse at Reading. They found that the rate of floral development was enhanced by warmer nutrient solution temperatures at the same air temperature and times to panicle emergence were reduced by an average of 17 days with increase in the nutrient solution temperature from 20 to 28°C. They stressed on the importance of determining water/root temperature as well as air temperature when investigating the effect of environment on development of the rice plant.

Dingkuhn and Miezani (1995) and Dingkuhn *et al.* (1995) studied the climatic determinants of irrigated rice performance in the Sahel. They reported that locally grown varieties were mostly of medium duration and comparatively thermo- and photoperiod-insensitive. They further reported that minimum temperatures below 18°C at booting stage resulted in near total spikelet sterility and a specific delay in heading.

Kawakata and Yajima (1995) used nonparametric methods to develop an equation describing the number of days required from

emergence to flowering as a function of air temperature, photoperiod and sowing date in Japan. Six rice cultivars were sown at 2 weekly intervals during one year, in a greenhouse maintained at a constant air temperature (average 24.4°C). The number of days required from emergence to flowering was constant for rice plants sown between August and February, while those sown between March and July required more time. On the basis of these results, an equation describing the cumulative water temperature over the time required for flowering as a function of photoperiod ($f(P)$) and sowing date was derived. The value of $f(P)$ was almost zero when the photoperiod was shorter than the critical photoperiod (P_0); when the photoperiod was longer, however, the value of $f(P)$ increased proportionally. The function was simplified to represent the effective photoperiod. The equations of this model were able to analyse quantitatively the photoperiod sensitivity of rice plants and the observed flowering time was accurately estimated.

Mahmood (1997) studied the impacts of air temperature variations on the rice phenology in USA. He reported that the prevailing air temperature determined the length of crop growth stages. He reported that the planting date plays an important role in the boro rice phenology. This effect was most noticeable during initial growth stages. A non-linear relationship was found between decreasing air temperature and the length of the initial growth stage and a predominantly linear relationship was found with other growth stages. Model applications showed that an increase in air temperature provides longer and more stable thermal conditions for boro rice maturing stage. A 5% increase and a 4% decrease in seasonal total evapotranspiration occur under each 1°C cooler and warmer air temperature conditions, respectively.

Rai and Chandrahas (1997) reported that the relative humidity and number of rainy days were beneficial up to early growth phase whereas

sunshine and maximum temperature in addition to relative humidity contributed positively towards rice yield up to the vegetative phase. During the reproductive phase, minimum temperature and rainfall had the deleterious effect on the yield of rice.

Sie *et al.* (1998) developed and tested an empirically based model for estimating rice crop duration and leaf appearance rate in a variable thermal environment in Senegal. They reported that the rate of leaf appearance was dependent on the temperature above base temperature. Mean daily water temperature (T_w) varied from 13 to 35°C. After seed soaking, the rate at which the first leaf (L1) appeared was linearly related with T_w , with a base temperature (T_{base}) of about 10°C. Appearance rates of the subsequent three leaves (L2-L4) had a similar T_{base} , and presented a distinct temperature optimum (T_{opt}) at about 23°C, beyond which development rates decreased. No significant temperature response was observed for the leaf appearances between L5 to the flag leaf (L12 to L20). Crop duration to flowering varied from 45 (IR-64) to 63 days (Jaya). These variations were associated with highly variable leaf numbers in all cultivars, including photoperiod-insensitive cv. IKP. One-third of the variable duration was due to a variable basic vegetative phase (BVP), caused by variable germination and leaf appearance rates and two-thirds due to variable duration of panicle induction after BVP. Water temperature was the main determinant of both sources of variability. The model was used to identify phonological stage and cultivar-specific causes of variable crop duration.

Yin and Kropff (1998) conducted a greenhouse experiment. Plants of 12 rice (*Oryza sativa*) cultivars were grown under three short-day (SD) conditions (10, 11 or 12 h day⁻¹) or under three long-day (LD) conditions (13, 14 or 15 h day⁻¹) until panicle initiation (PI), after which half of the plants at SD were transferred to a 3 h longer photoperiod and half of the

plants at LD were moved to a 3 h shorter photoperiod. Duration from PI to flowering was positively correlated with the photoperiod experienced after PI; the effect of a 3 h change in photoperiod varied from negligible in some cases to more than 10 days in others. No consistent carryover effect of photoperiod before PI on the PI to flowering duration was detected. As expected, the total main-culm leaf number was influenced by photoperiod before PI, but not thereafter. Although the leaf number varied greatly both among cultivars and among pre-PI photoperiods, the number of unexpanded leaves at PI was nearly constant, with an average of about three leaves. This study further supports an earlier experimental finding that rice photoperiod sensitivity continues some days after PI, suggesting the inadequacy of the assumption in crop simulation model CERES-Rice that the PI to flowering duration is influenced only by a carryover effect of pre-PI photoperiod.

Rai and Chandrahas (1999) used linear discriminate score of weather parameters and input variables for forecasting of rice yield. They observed that temperature (maximum and minimum) and sunshine hours were effective at the growing phase whereas sunshine hours found ineffective during early growth phase. All the variables under study at active vegetative phase explained about 87% of the total variation in rice yield.

Lalitha *et al.* (2000) studied the influence of temperature on duration of tillering in lowland rice varieties in Andhra Pradesh. They reported that temperature prevailing during tillering period controlled its duration. Daily mean temperature exceeding 26°C during period of tillering restricted the durations to 5 weeks after planting whereas the temperature in the range 22.9 to 25.8°C increased the duration up to 8 weeks. They concluded that the period taken to attain maximum tillering stage could be predicted by using degree day concept.

Goswami *et al.* (2003) calculated growing degree days for rice and wheat in Ludhiana by summing mean daily temperature above base temperatures. The base temperature for wheat was 4.4°C and 10°C for rice. The sowing of rice nursery was done on May 12 and the transplanting was undertaken 30 DAS. Tillering started 39 DAS. The two rice varieties (PR 111 and PR 114) attained the physiological maturity on 124 and 128 DAS respectively. They reported that the phenological events followed the same trend irrespective of variety. GDD for PR 114 were relatively higher due to longer duration of the variety.

Kumar and Sharma (2004) used the CERES-Rice model to simulate the growth, development and yield of four different rice cultivars (RP 2421, HPR 927, HPR 957 and Kasturi). The model was efficient in predicting the phenology of all cultivars and the association between actual and simulated data on number of days to flowering and physiological maturity was significant.

Rai and Kushwaha (2005) reported that the simulated and observed values for number of days to panicle initiation and 50% flowering coincided in case of rice cultivar under Pantnagar, Uttaranchal, whereas the estimated value for number of days to maturity was higher than the simulated value. A high correlation between the observed and simulated value for yield and yield components including number of panicles, number of grains per panicle and 1000-grain weight was recorded, indicating the suitability of the CERES-Rice model in simulating the development, yield and yield components of upland rice.

2.3. Effects of date of transplanting or sowing on growth and yield of rice

Adjustment of date of transplanting can be attained by trial and error method by transplanting rice crop on different periods of year.

Appropriate transplanting or sowing time of the crop is the best way to adjust to the suitable weather conditions for attainment of different phenological phases of the crop. Viswambharan *et al.* (1987) developed linear regression models to predict yields of rice cultivars in relation to weather components in Kerala by conducting a field trial during 1983-86. Rice cv. Jaya and IR-8 were transplanted on 7 dates between 22 August and 12 November. Grain yield was positively correlated with total solar radiation during 5 to 15 days before the 50% heading stage, and negatively correlated with the number of rainy days 15 to 30 days before the 50% heading stage. Adverse effects of weather on yield were more pronounced in crops transplanted from 18 September to 17 October.

Mondal and Chatterjee (1973a) working in moist sub-humid tropics of West Bengal on IR-8 and Jaya rice sown at monthly interval reported that in both varieties tillering was high in the bright weather of summer months. The rate of production of tillers was slow in winter. The rate of leaf production on the main stem was slower in winter months than in other months. Thus, growth continued for a longer duration when transplanted in September or October (200 to 220 days) than those planted in other months (120 to 140 days). At flowering the leaf area indices ranged from 5 to 6 in wet season; it ranged from 3.5 to 5 in dry season (January to February planted crops) and 2 to 4 in September to November planted crops. From another study they reported that yields were very low in crops that were transplanted in late August to late December. Cool season at the time of panicle initiation and development of spikelets badly affected the yield due to lesser number of panicles per unit area and increased number of unfilled grains. Crops that matured in sunny bright days (April-May) yielded higher than those maturing in wet season. An analysis of physiological basis of yield differences revealed that low

yields in winter were mainly due to low leaf area duration (LAD) of crops transplanted in September to November (Mondal and Chatterjee, 1973b)

Ramakrishnan and Subbiah (1979) found out the influence of time of sowing on the yield of rice. Paddy yields were higher in rice cv. Kannagi sown on 30 June than when sown on 15 June or 15 July; in cv. Vaigai they were higher when it was sown on 30 June or 15 July. Souza *et al.* (1980) measured the duration of various growth stages in 32 lines and cultivars of rice sown on 16 October, 30 October or 30 November in 1979. Delay in sowing decreased the duration of the growth phases, especially the vegetative phase.

Infeld (1980a,b) reported from a field trial with six rice cultivars sown on 12, 19 or 31 October, 15 November, or 1 or 12 December, 1979 that sterility of rice is influenced by date of sowing. Grain yields generally decreased with the latest sowing date and were highest with an intermediate sowing date. The percentage sterility was investigated in relation to minimum temperature and it was concluded that in the season 1979-80, low temperature was not a cause of sterility.

Roy and Biswas (1980) found out the effect of date of sowing on the yield of boro rice. When rice was sown in the Gangetic plains on (a) 12 November, (b) 26 November, or (c) 10 December, seedling height, plant dry matter (DM) content, number of fertile tillers plant⁻¹ and crop duration decreased with delayed sowing and decreasing minimum day and night temperature. Grain yield was reduced by 22% and 30% after delaying sowing from 12 to 26 November and 10 December respectively. Low temperature reduced seedling leaf emergence by up to 30 days.

Chaudhary and Nazimi (1982) working on rice cv. Kashmir Basmati, Krasnodorsky, Calrose, Gritna and Sarikilcik sown in West Turkey at 10 day intervals from 2 April to 11 June, 1979 observed that

duration of vegetative period decreased from 101 days from the 1st sowing date to 84 days from the last sowing date and varied according to cultivar. Floret sterility increased from the 2nd sowing date to the last sowing date. Sowing date x cultivar interactions significantly affected sterility and temperature of <15°C within 12 h of anthesis caused a high rate of floret sterility possibly through indehiscence of anthers or pollen grains not germinating. Cultivar Calrose and Kashmir Basmati were least affected by low temperature, but had the longest vegetative periods, averaging 113 and 106 days, respectively.

Khan (1982) showed that shifting the date of sowing from month to month greatly altered the time of flowering in mid winter rice cv. BAM 11. Plants sown in January flowered in April. Plants sown from February to August flowered in October. September- sown plants flowered in November; and those sown in October flowered in December, those sown in November and December flowered in February and March, respectively, in the following year. Short-day treated plants flowered remarkably earlier than the corresponding controls in all months of the year irrespective of the month of sowing.

Patrohardjono *et al.* (1982) showed that when IR 36 was transplanted at monthly interval between August 1979 and July 1980 at 2 locations, lower grain yields (3.12-3.33 t ha⁻¹) were obtained from the October, November and December transplanting, as against the maximum yield of 4.64 from June transplanted crop grown at Muara. Yield was affected by the ripened grain percentage and grain sterility but not by spikelet numbers/unit area or 1000 grain weight. There was a close correlation ($r = 0.739$) at Muara between solar radiation during the ripening period and the net assimilation rate which in turn affected dry matter production.

Urkurkar (1983) working on rice cv. Asha planted during the 1981 monsoon season on 10 dates at 10 day intervals between 1 June and 30 August reported that optimum yields were obtained by transplanting between 11 and 21 July. Water use efficiency for grain yield was highest for rice transplanted between 11 and 31 July, while water use efficiency for dry matter (DM) was highest between 11 and 21 July. Grain yields were higher with higher radiation.

Chaudhary (1984) conducting trials with the rice cultivars sown at Izmir on seven dates (2 April to 1 June) in two years concluded that Calrose gave the highest average grain yield. There was a significant sowing date x cultivar interaction effect on yield and duration. The long duration cv. Calrose (short grain), Kashmir Basmati and Labelle (high quality) performed best if sown in April. Late sowing reduced yield less in the medium duration cultivar Gritna than in short-duration Krasnodorsky and Maratelli.

Reddy and Reddy (1986) reported that transplanting of four Nellore rice cultivars between 5 and 20 September gave higher paddy yields than transplanting in August or October. The duration of the crop decreased with delay in planting, but the production/day was increased. Harvest index increased in the crops transplanted between 5 September and 5 October, while it decreased in crops planted on 20 August and 20 October.

Roy (1987) observed in the field trial with rice sown on July 13 and August 10 and then transplanted, days to heading, total grains/panicle and 1000 grain weight differed significantly among lines with sowing date. Although plant height, filled grains/panicle and yield were reduced by an average of 19.0, 19.8 and 38.5% with August sowing, effective tiller number and 1000 grain weight were increased by 37.5 and 3.6%

respectively. Number of days to heading was 102 to 111 with July sowing and 87 to 101 with August sowing. Average temperature was 26.5°C during panicle initiation for the July sowing and 23.3°C for the August sowing; the average temperatures during grain filling were 22 and 20°C respectively. Sterility was 22 % for the August sowing and 19% for July sowing crop.

Maity and Mahapatra (1988) reported that transplanting on 5 to 10 January and 20 to 25 December gave highest yields of 3.7 and 2.6 t ha⁻¹ in 1985 and 1986, respectively. Late and early transplanting reduced yield, probably because of higher temperature.

Ghosh *et al.* (1988) reported that the incidence of spikelet sterility was markedly higher in late-sown (16 August) crops than in those sown on the normal date (16 June). Cultivars differed in spikelet sterility caused by the low temperature in the late sown crops. Cv. Br 34, Janki and Darmi were tolerant of low temperature at flowering and showed the lowest percentage of spikelet sterility.

Babu (1989) analysed the effect of planting time and variety on growth and yield of rice and reported that MTU 7029 and MTU 5249 gave higher yields (3.9 to 4.3 t) than the other 2 cultivars (2.8 to 3.3 t) when transplanted on 30 July, while BPT 2740 gave higher yields than other cultivars when transplanted on 15 and 30 September.

Kulkarni *et al.* (1989) reported significant differences for days to 50% flowering, productive tillers/m², sterility and grain yield between two rice cultivars (Tella Hamsa and Pothana) sown at fortnightly intervals from 15 November to 15 January at Warangal. The number of days to 50 % flowering decreased as sowing was delayed. Spikelet sterility was greater in Pothana than in Tella Hamsa and was higher at early sowings when minimum temperature before flowering was <19.6°C and gradually

decreased in later sowing when temperature before flowering were 21 to 22°C.

Kim *et al.* (1991) reported the number of days to emergence decreased from 13 days for 10 May sowing to 7 days for 10 June sowing at Yeongnam, Korea, but the cumulative temperature for emergence was stable at 110°C. The practical earliest sowing date was 5 May with 15 d to emergence. The period from sowing to heading also decreased with delay in sowing with an effective cumulative temperature of 871 degrees for Donghaebyeon, 891 degrees for Nagdongbyeon and 912 degrees for Milyang 95. The critical last sowing dates based on the cumulative temperature for ripening were 25 June for Odaebyeon, 20 June for Keumbyeon, 5 June for Donghaebyeon, 30 May for Palgongbyeon, 25 May for Nagdongbyeon and 20 May for Milyang 95. Delayed sowing resulted in reduced culm length, panicle length, spikelet number and grain yield.

Mohapatra and Kar (1991) reported that mean grain yields of CR-1009 variety of rice were 3.88, 3.82, 3.63 and 3.43 t ha⁻¹ when transplanted on 16 July, 31 July, 15 August and 30 August, respectively at North Eastern coastal plains of Orissa. Differences in yield of various dates of transplanting were due to differences in panicles m⁻² and grains panicle⁻¹. Early transplanting also slightly but significantly increased 1000 grain weight.

Paul (1993) reported that when rice cv. IET 6666 transplanted on 5 or 20 July, 4 or 19 August or 20 September at Gossaigaon in Assam, grain yield increased with delay in sowing until 20 July after which it decreased; transplanting on 2 September gave 0.26 t ha⁻¹ compared with 3.07 t ha⁻¹ from transplanting on 20 July.

Om *et al.* (1993) showed from a field experiment conducted at Kaul, Haryana with rice cv. Basmati 370 transplanted on 25 June, 5, 15 or 25 July

or 4 August that grain yields of 4.29, 4.09, 3.85, 3.67 and 3.45 t ha⁻¹, respectively. The decrease in yield through delaying transplanting was due to reduction in panicles/ hill and grains/panicle.

Lakpale *et al.* (1994) conducted a field experiment during the rainy seasons of 1990-91 at Raipur, Madhya Pradesh with 3 rice cultivars and reported that the optimum sowing date was the 3rd week in July; sowing earlier decreased grain yields. Panda *et al.*, (1996) studied the management of rice cv. Lalat for the aberrant weather situations of the coastal plains of Orissa taking four transplanting dates at 10-d intervals starting from 20 August and three spacings (10 x 10, 15 x 10 and 20 x 10 cm). They outlined contingent planting of rice for aberrant weather situations in Coastal Plains of Orissa. They reported that late transplanting decreased grain yield significantly from 50.05 q/ha (20 August) to 20.0 q ha⁻¹ (19 September). Reduction in cumulative temperature of 195.9, 302.5 and 534.9°C in the main field decreased the grain yield by 18.22, 33.41 and 60.03%, respectively. Spacing at 10 x 10 cm produced the highest mean yield of 38.84 q ha⁻¹.

Lee and Lee (1997) showed the effect of dates of planting on yield potential of rice transplanted on 4 or 25 August or 16 September 1995 and on 7 or 21 August or 5 September 1996. Yield decreased as transplanting was delayed, associated with delayed heading, decreased plant height, yield components and shortened growth duration. Low temperatures and reduced solar radiation decreased both vegetative and reproductive growth and inhibited panicle heading with delayed transplanting, particularly in September.

Hundal and Kaur (1999) used dynamic rice growth and yield CERES-Rice' simulation model as a tool to evaluate various agronomic practices in rice production under the conditions of Indian Punjab. The effects of various dates of transplanting, age of seedlings at transplanting,

number of seedlings/ hill and plant population on rice (cv. PR-106) yields were simulated. The simulation results showed that the optimum date of transplanting for rice was 15 June. However, earlier transplanted (1 June) rice may perform better if seedling age is reduced from 40 to 30 days. Young seedlings (20 and 30 days old), irrespective of date of transplanting, proved better than older (40 days) seedlings, when other variables were kept constant. An increase in plant population from 11 to 44 hills m⁻² and an increase in number of seedlings/hill from 1 to 6, showed an increasing trend in rice yields as simulated by the model.

Patel (1999) reported that planting dates significantly influenced yield and yield attributes of rice. Maximum grain yield was obtained when the crop was transplanted on 15 July. The yield decreased significantly with delayed planting on 30 July and 14 August by 15.8 and 27.8% in 1992 and 18.8 and 30.6% in 1993, respectively. The same trend was also observed in straw yield and yield attributing characters viz., number of total tillers and panicles m⁻², grains/panicle and weight of 1000 grains.

Begum *et al.* (2000) observed that date of transplanting greatly altered the time of anthesis, maturity and finally, the total duration of both varieties in Bangladesh with 10 dates of sowing, starting with 1 July, 1994 and ending with 28 March, 1995 at 30 days interval with two rice varieties. It was observed by them that in both the varieties, transplanted on 29 September and 29 October field durations prolonged and the longest field duration was of 187 days in both the varieties transplanted on 29 October.

Slaton *et al.* (2003) reported that the sowing date has a substantial influence on rice (*Oryza sativa*) grain yield and observed that the rice grain yields decrease as the date of seeding is delayed across the mid-south rice-producing area in the USA. However, information quantifying

the rate of yield decline has not been developed. Rice sown during the optimum period had a longer vegetative growth phase than later sown rice.

Ghosh *et al.* (2004) documented that growth environment and plant nutrition are two important factors influencing growth, yield and quality of aromatic rice (*Oryza sativa* L.) after conducting an experiment to determine the effect of two planting dates and four fertilizer levels on different aromatic rice cultivars during the dry seasons of 1995-96 and 1996-97, while nine cultivars were evaluated during the wet seasons of 1996 and 1997 at Kalyani. They reported that the thermal and photoperiodic conditions significantly influenced the vegetative (leaf area index and light extinction co-efficient) and reproductive (filled spikelets/panicle) growth of the crop. Delayed planting (23 February) significantly reduced the grain yield by 0.88 t ha⁻¹, amylose content by 0.5% and duration by 10 days; but increased the summed heliothermal units (17806 to 18505). Thus, the cultivars became less efficient (27%) in heat use with delay in planting from 2 to 23 February. Relative availability of NH₄⁺-N from urea and Azolla influenced the crop growth (leaf area index, tiller production and leaf chlorophyll content) and nutrient uptake. Supply of inorganic N either alone or in conjunction with Azolla significantly increased grain yield (18 to 41%) and protein content (0.1 to 0.7%) over 15 t ha⁻¹ of Azolla alone. However, combined application of Azolla and urea lowered the amylose content below that achieved by application of either substance alone. Correlation studies among quality attributes indicated that long-grained varieties had lower head rice recovery ($r=-0.69$) due to more breakage during milling and greater test weight ($r=0.93$).

2.4. Crop growth models

A model is a simplified representation of a system and simulation is the study of the system and its behaviour using model. CERES-Rice is a comprehensive model that simulates the phasic development of a rice crop, the growth of its leaves, stems, roots and panicles, and their response to weather conditions. It also simulates the water and N balances of the crop and the effects of stresses of water and N on the yield forming processes. Thus, crop models are useful tools for considering the complex interactions between a range of factors that affect crop performance, including weather, soil properties and management. Where pests and diseases are controlled, water and nitrogen fertiliser management are the main factors influencing yield for a given environment.

2.4.1. Types of the model

Passioura (1973) broadly classified two types of the crop models as follows:-

- (i) Functional model: It is a practical model, which combines the thumb rules to predict the behaviour of crops.
- (ii) Mechanistic model: This type of model represents the biological and physiological processes, which occur in the plants and their environments.

Baier (1979) proposed a classification of models on the basis of time scale, data source, approach, purpose and application. Using these features three groups of models have been suggested as follows:-

- (i) Crop growth simulation models that consider the impact of meteorological variables on specific plant processes which could be adequately simulated by means of a set of mathematical equations that are based on available knowledge of the particular process or experiment.

- (ii) Crop weather analysis models, which produce a running account of the accumulated daily crop response to selected agrometeorological variables as a function of time (crop development).
- (iii) Empirical statistical models in which one or several variables representing weather or climate, soil characteristics or time trend are statistically related mostly to seasonal yield or crop production statistics.

The crop models have also been classified by Whistler *et al.* (1986) into various categories as follows:-

- (1) Empirical or correlative models that describe the relationship between variables without referring to any underlying biological or physical structure that may exist between variables.
- (2) Mechanistic or explanatory models explicitly represent the known or hypothesized mechanisms that relate variables and explain their observed behaviour. These models represent causality between variables.
- (3) Stochastic models are based upon the probability of occurrence of some events or exogenous variable.
- (4) Deterministic (physiologically, physically based simulation) models are those models by which whose plant or soil processes can be physiologically, physically or chemically described.
- (5) Static model (phenological model) is a broad class of models that predict crop development from one growth stage to another.
- (6) Dynamic simulation crop models predict changes in crop status with time as a function of exogenous parameters.

Methods of predicting crop yields range from statistical approaches (Gangopadhyaya and Sarkar, 1964; Haun, 1974; Rao, 1977; Stewart and Dwyer, 1990) to crop simulation models (Duchon, 1986; Aggarwal and

Kalra, 1994a; Hundal and Kaur, 1997). Despite several classifications put forth by the research workers, it is more convenient to categorize the crop models broadly into two categories, namely empirical/regression models which lie beyond the scope of interest of the present investigation and crop simulation models.

2.5. Crop simulation models

Crop growth is a very complex phenomenon and product of series of complicated interactions of soil, plant and weather. Dynamic crop growth simulation is a relatively recent technique that facilitates quantitative understanding of the effects of these factors and agronomic management factors on crop growth and productivity. These models are quantitative description of the mechanism and processes that result in growth of the crop. The processes could be crop physiological, meteorological, physical and chemical processes. Such a modeling assumes that the rate of change of system can be closely approximated by considering the rate of processes to be constant during short time periods. This is based on state variable approach in which current states (for example, weight of plants, evapotranspiration, leaf area index) are updated after every short interval (usually one day) considering the previous state and the rate which is influenced by internal crop properties and environment. This is repeated till the crop is mature. Model that deal with crop growth simulation can be distinguished in to two categories: Descriptive and Explanatory.

Descriptive models defined the behaviour of a system in a simple manner. These models show the existence of relation between the elements of a system but reflect very little, if at all. Of the mechanisms involved underlying the behaviour of that system. A very simple example of a descriptive model has been documented by Sibma (1987), where the biomass production of maize under optimum conditions as a function of a

time has been modeled using a simple regression equation. The model fits the data for that year very well but it fails totally for others years which highlights the limitations of descriptive models. It is always possible to add more variables (Agrawal and Jain, 1982) and improve the estimates but in the absence of any quantitative relationship of the processes contributing towards dry matter production would always be suspect as for maize. The scope for incorporating the effect of management practices is limited in such models.

Explanatory models consist of quantitative descriptions of the mechanisms and processes involved that are responsible for the behaviour of the system. For an explanatory model the system is analyzed and its processes and mechanisms are quantified separately. The model is then built by integrating these descriptions for the entire system.

Explanatory models are means by which, knowledge about systems and their performances is made portable and accessible to users whose livelihood and welfare depend on the systems performance. Models are extremely useful because the critical environmental problems caused by agricultural practices are system problems not disciplinary ones. Their solution demands a multi disciplinary approach linking basic and applied sciences. The behaviour of a crop growth model can be explained by the basic physiological, physical and chemical processes and the effects of environmental factors on them.

Over the past 50 years, workers in the disciplines of biology, physics and engineering have contributed in characteristic ways to the development of crop simulation models. "System" approach successfully used by engineers to simulate physical system provided an early anticipation that biophysical systems could also be simulated. According to systems approach, a system is a limited part of reality that contains

interrelated elements. The totality of relations within a system is known as the "System structure".

Crop simulation modeling started in early 1960s when early simple crop models were developed for estimation of transpiration and photosynthesis. The first step towards crop modeling was the development of simple models to estimate light interception and photosynthesis (Loomis and Williams, 1963; de Wit, 1965; Duncan *et al.*, 1967). These simple models were used to quantify the light profile in a canopy and to assess the sensitivity of crop photosynthetic rates.

Last two decades witnessed the development of numerous crop-weather models describing the dynamics of the soil-water-plant-atmosphere system. These are becoming increasingly indispensable tools for quantifying physical, chemical and biological processes in the agro-eco system. Crop models are covering wide range of crops and are applicable to study the crop production under limited water availability and irrigation condition both (Kundu *et al.*, 1982).

Angus and Zandstra (1980) developed a crop simulation model for rainfed wetland rice incorporating the effect of radiation, moisture, temperature and nitrogen on plant growth. Penning de Vries *et al.* (1989) presented the physiological based crop growth model as a part of the Simulation and System Analysis for Rice Production (SARP) project. WTGROWS, a wheat growth model was developed by Aggarwal and Kalra (1994b) for simulating the potential yield of wheat crop and latitudinal effect on yield of wheat in India. In India, crop growth model development studies started in late 1980s by Ritchie and Algarwamy (1989), Rao (1992) developed BRASSICA model and Singh and Virmani (1996) developed CHIKPGRO model.

During 1960s and 1970s, scientists started recording biometric information in computer database, which enabled rapid searches to be

made for data on plants. At the same time scientists started making computer models of how plant grows. This led to the production of formal growth prediction systems for the world's major crops (maize model by Jones and Kiniry, 1986). Later, with help of the computers and tremendous advances in equipment for field measurements, modeling of many processes/factors that influence crop yield, came into vogue.

Mall and Aggarwal (2002) reported the results of a comparison of two popular rice growth models, CERES-Rice and ORYZA1N, for the same input conditions. Both models use different approaches for simulating growth and yield, are sensitive to climate change parameters, and represent two major schools of crop modelling. A dataset of 32 experiments consisting of 98 treatments was assembled from an extensive literature search. These experiments were conducted over the period of 1980-1993 in diverse Indian locations from 11 to 33 °N. The treatments varied in N management, sowing dates, cultivars and seasons. The flowering duration in the dataset varied between 37 and 86 days and grain yields between 2587 and 8877 kg ha⁻¹. Seven treatments from this dataset, one for each cultivar, were selected for calibration. The genetic coefficients of different cultivars used in the analysis for both models were estimated from this short-listed dataset by repeated iterations until a close match between simulated and observed phenology and yield was obtained in these treatments. Similarly, 11 treatments with zero or low N applications were used for calibration of initial soil N for different locations. The remaining 80 treatments were used for validation of the models. Both models predicted satisfactorily the trends of leaf area and dry matter growth, grain number, days to flowering and grain yields. Simulated yields were within $\pm 15\%$ of the measurements. Considering that the field measurements also generally have 10 to 15% error and that the treatments widely varied in weather conditions, particularly in

temperature, it was concluded that both models are adequate to simulate the effects of climate change on rice yields in diverse agro-environments of India that are free from all pests.

Timsina and Humphreys (2006) reviewed the performance of CERES-Rice and CERES-Wheat in Asia and Australia in relation to their potential application towards increasing resource use efficiency and yield of rice wheat systems. Crop models potentially offer a means to readily explore management options to increase yield, to determine trade-off between yield, resource-use efficiency and environmental outcomes. The performance of the models was evaluated using simulated and observed data on anthesis and maturity dates, in-season LAI and growth, final grain yield and its components, soil water and N balances from published studies across Asia and Australia and then by computing the statistical parameters for the major characters. Over the four data sets examined for anthesis and six for maturity dates, CERES-Rice predicted those dates fairly well (normalized RMSE=4 to 5%; D-index=0.94 to 0.95), but over the 11 sets for grain and 4 for biomass yield, the predictions were more variable (normalized RMSE=23% for both; D-index 0.90 and 0.76, for grain and biomass, respectively). Model performance was poorer under conditions of low N, water deficit, and low temperatures during the reproductive stages. Over the three data sets examined, CERES-Wheat predicted the anthesis and maturity dates quite well (normalized RMSE=4 to 5%; D-index=0.94 to 0.99), and over eight sets for grain and two sets for biomass yield the model predicted them also reasonably well (RMSE=13 to 16%; D-index=0.86 to 0.97). Only one study evaluated the DSSAT rice wheat sequence model with fairly satisfactory predictions of rice and wheat yields over 20 years with adequate N, but not the long-term change in soil organic C and N. Predictions of in-season LAI and crop growth, soil and water processes were quite limited to investigate the robustness

of model processes. Application of models to evaluate options to increase water and N use efficiency requires the ability to perform well at the margin where deficit stress begins. While both models generally perform satisfactorily under water and N non-limiting conditions, the little evidence available suggests that they do not perform well under resource-limiting situations. They recommend that the model's key processes under the water and N limiting conditions be further evaluated urgently.

2.6. Applications of crop simulation models

Mathews and Stephens (2002) categorized the main applications or needs of models into 3 categories: as tools in research, in decision support, and in education and training. Examples of research applications included identification of desired crop genotype characteristics, investigation of management options, cropping or farming system analysis, investigations of impact of climate change on crop productivity, and prediction of greenhouse gas production. Models can be used to assist both tactical decision making such as irrigation scheduling, fertiliser and pest management, or in strategic decision making, such as planning for climate change or to avoid salinisation, yield forecasting and planning for national food requirements. Models can also be useful in teaching crop and soil processes and crop system behaviour in response to weather, management and site conditions. Though the review of pertinent heading has been mainly confined to application of CERES-Rice model, relevant research work on some other models has also been reviewed and relevant information included wherever necessary.

The applications of CERES-Rice identified in this review are summarised under seven categories: yield forecasting, yield gap and trends analyses, devising agronomic management strategies, extrapolation to other locations, impacts of climate change and government policy and strategic planning.

2.6.1. Yield forecasting

Reasonably precise estimates of acreage and yield before the actual harvest are of immense value in policy planning. The relatively small cost and speed of assessment makes crop growth simulation models promising for areas where significant daily weather data during the cropping season for the geographical region of interest. Weather data for typical years are used to continue simulation until harvest. Horie *et al.* (1992) showed an example where crop models, regional weather database and historical yield data is used to forecast rice yields for different regions of Japan.

Thornton *et al.* (1997) estimated the millet production for the thirty provinces of Burkina Faso, using CERES-Millet model. Provincial yields simulated halfway through the growing season were generally within 15% of their final (end-of-season) values. Shekh and Rao (1996) estimated the yield of maize crop at Anand using the CERES-maize simulation model. They reported that maize yield varied between 4.8 to 5.1 tha^{-1} at Anand in Gujarat state. Hodges *et al.* (1987) used CERES-Maize model and predicted of yield over 51 sites in the United States and estimated production for three years and reported that model approach was valuable for yield forecasting.

2.6.2. Yield gap analyses

An important role for crop models is the estimation of yield potential and yield gaps at site, regional and national levels, identification of reasons for the gaps and evaluation of management options for closing those gaps. CERES-Rice and Wheat have been used for determining potential yields and for identifying yield gaps in rice and wheat in many locations of many countries. The results generally reveal large gaps between potential yields and farmer yields. Jintrawat (1995) compared long-term yields with simulated yields using CERES-Rice for provinces in

north and northeast Thailand. Simulated yields were higher than provincial yields by 0.4 (north) and 1 t ha⁻¹ (north east) due to losses caused by insects, diseases, rodents, and lodging. Boonjung (2000) also estimated potential yields of rice in Thailand, finding lower potential yields in the northeast (2 t ha⁻¹) than in the southwest (3.2 t ha⁻¹), and with greater yield variability in the northeast. In West Java, farmer's yields ranged from 4.0 to 4.1 t ha⁻¹ while simulated yields ranged from 4.4 to 4.7 t ha⁻¹, suggesting a small yield gap in this part of Indonesia.

Pinnschmidt *et al.* (1997) estimated weather-limited and weather plus N-limited yields using CERES-Rice v.2.1. The difference between observed and weather-limited simulated yields averaged about 35% in the Philippines, 45% in Vietnam, and 55% in Thailand. The gaps were mainly due to N limitation in Thailand, where soil N and fertilizer use are low. In the other two countries the gaps were mainly due to other constraints including low soil organic carbon, water deficit, disease and pest damage and partly due to low N.

Timsina *et al.* (1997) estimated long term (1979-1992) rice-wheat system potential yields, and yields at 120 kg N ha⁻¹ (recommended N) and zero N using rice cv. Jaya and Pant-4 and wheat cv. RR 21 and UP 262 at Pantnagar. Potential yields of the rice cultivars for 1979-1992 with 150 kg N ha⁻¹, varied from 4 to 8 t ha⁻¹, and were 0.5 to 2 t ha⁻¹ higher than the yields at 120 kg N ha⁻¹. In wheat, however, long term potential yields and yields at 120 kg N ha⁻¹ were similar and varied from 4.5 to 5.7 t ha⁻¹. The study suggested considerable gaps between yield potential and yields being achieved by researchers for rice but not for wheat in rice-wheat systems of Pantnagar.

Saseendran *et al.* (1998b) reported average potential yield using CERES-Rice v.3.0, across four transplanting dates of 15.4 t ha⁻¹ for cv. Jaya in Kerala, compared with average actual yields of 5.2 t ha⁻¹ under rainfed

and sub-optimal N management practices. The very large yield gaps in Kerala suggested the need for capturing and storing the surplus rainwater during the rainy season for irrigating crops during the non-rainy periods using CERES-Wheat v.3.0

Aggarwal *et al.* (2000a) determined potential yield of 16.0 t ha⁻¹ (rice 9.0 t ha⁻¹ and wheat 7.0 t ha⁻¹) for Delhi using CERES-Rice and CERES-Wheat as stand alone models. These potential yields are much higher than the national average rice-wheat system yields in long-term experiments (8.1 t ha⁻¹) or the Punjab average systems yield (7 to 8 t ha⁻¹).

2.6.3. Yield trend analysis

Yield stagnation or decline in rice and wheat grown separately or in sequence is a concern for food security in south Asia. Aggarwal *et al.* (2000a) used ORYZA1N and CERES-Rice to predict yield trends of rice and CERES-Wheat and WTGROWS for wheat for several districts in North East India. Measured district rice yields declined in many districts (Karnal, Gurdaspur, Kapurthala, Ludhiana, and Sangrur) but increased in others (Kurukshetra and Amritsar). Wheat yields increased over time in all districts, but at a slower rate in recent years compared with the previous decade. The decline in rice yields observed in a long-term experiment in Ludhiana was also predicted by CERES-Rice, but not by ORYZA1N. For wheat, however, both models predicted yield trends 19 consistent with the observed trends. Pathak *et al.* (2003) also compared measured district rice and wheat yields with potential yields predicted using CERES-Rice and CERES-Wheat for several districts (Ludhiana, Karnal, Delhi, Kanpur, Varanasi, Faizabad, 24-Pargana, Raipur and Pantnagar) in India. The district average yields of rice varied from 2.1 t ha⁻¹ at Raipur to 5.6 t ha⁻¹ at Ludhiana, and yields of wheat varied from 1.0 t ha⁻¹ at Raipur to 4.3 t ha⁻¹ at Ludhiana. Long-term (1985-1989) potential rice yields ranged from 7.7 t ha⁻¹ at Raipur to 10.7 t ha⁻¹ at

Ludhiana, while potential wheat yields ranged from 5.2 t ha⁻¹ at 24-Pargana to 7.9 t ha⁻¹ at Ludhiana. The average annual change in potential yield of rice ranged from -0.12 t ha⁻¹ yr⁻¹ in Delhi to 0.05 t ha⁻¹ yr⁻¹ in Kanpur, with significant trends for yield decline in 4 out of 9 districts. The rate of annual wheat yield change ranged from -0.07 t ha⁻¹ yr⁻¹ in Delhi to 0.04 t ha⁻¹ yr⁻¹ at Faizabad and Pantnagar, none of the yield changes being significant. Models suitable for examining long-term yield trends require the capacity to address issues related to carryover of soil organic matter and nutrients between each phase of the cropping system.

Timsina *et al.* (1996) used the CERES-Rice and Wheat models embedded within DSSAT v.3.0 to explain the yield trends in rice and wheat in along-term rice-wheat experiment at Pantnagar, India. There was a clear trend of decreasing rice yields over 20 years, especially since year 11, and the decline was greatest for the control (zero N) and least for the 120 kg N/ha treatment. Wheat yields, on the other hand, consistently increased over time, with the greatest increase with 120 kg N/ha and least for zero N (Timsina *et al.*, 1995, 1996). Linear regressions of year against simulated yield suggested that rice yield declined and wheat yield increased. The reasons for the predicted yield trends are not known. Regressions of year number against simulated soil organic N and C for 120 kg N ha⁻¹ showed a steep decline in soil organic C and N over time (Timsina *et al.*, 1996).

2.6.4. Devising agronomic management strategies

CERES models have been used in devising tactical management strategies such as optimum sowing dates of wheat, transplanting dates of rice, plant population for rice and N management strategies in rice and wheat in several Asian countries.

Singh and Thornton (1992) used CERES-Rice to evaluate the effect of urea application method on N loss and efficiency for dry season rice at

Pila, Philippines. They compared broadcasting into 5 cm of floodwater, moderate incorporation in the soil without floodwater with a mixing efficiency of 30% and deep-point placement without floodwater with a mixing efficiency of 95%. The floodwater in the two latter cases was raised to 5 cm depth shortly after fertilizer application. The model predicted rapid and interactive transformations in the floodwater within two days of fertilizer application in the broadcast and moderately incorporated treatments and little fertilizer N reaction in the floodwater in the deep-placed urea treatment. The biological (algal) activity and biological transformations leading to higher floodwater pH were rapid in the broadcast treatment; consequently ammonia volatilization was also higher. Nitrogen losses declined with increasing degree of incorporation and were negligible when urea was deep-point placed.

Buresh *et al.* (1991) also used CERES-Rice to assess year to year variability in response to N application for two transplanting dates (15 January and 15 July) in Philippines. The model consistently predicted higher N response with the January than July transplanting and greater NH_3 loss for July than January transplanting. Timsina *et al.* (1995) investigated optimum transplanting date for rice at Pantnagar using the CERES models. Simulated rice yields were highest for early transplanting (13 June to 13 July) and lowest for late transplanting (27 August). Timsina *et al.* (1997) also used CERES models to identify the optimum planting dates for a range of cultivars of rice for several locations in Nepal. The optimum transplanting date was 15 May for most locations.

Saseendran *et al.* (1998a,b) also identified the optimum transplanting dates for rice (cv.s Jaya and IR 8) under rainfed conditions for five sites in Kerala, India. If only one crop were to be grown per year, the optimum transplanting dates would be later (4th week of June at one

site and 1st week of July for four sites), but if two crops were grown, the dates would be earlier (1st to 4th week of June for all sites).

Hundal and Kaur (1999) evaluated the age of seedlings at transplanting, number of seedlings per hill, number of hills m⁻² and date of transplanting for rice in the Indian Punjab. CERES-Rice predicted that the optimum date of rice transplanting was 15 June, but that earlier-transplanted (1 June) rice would perform better if seedling age were reduced from 40 to 30 days. Increasing plant population from 11 to 44 hills/m² decreased yield while increasing the number of seedlings per hill from 1 to 6 increased yield. Young seedlings (20 to 30 d old) gave better yields than old seedlings (40 d old).

Boonjung (2000) identified the optimum transplanting date of rice cv. KDML 105 (photosensitive) to be 1 to 15 June in Nakhon Ratchasima province in North East Thailand. Jintrawat (1995) applied CERES-Rice to develop long-term strategies related to planting dates, planting methods (dry-seeded rice, or transplanted rice), organic residue rates, N rates, water regimes (rainfed or irrigated) and soil types using cumulative probability functions. Strategic analysis was done for various combinations of management practices using 10 to 50 years of historical weather data.

2.6.5. Extrapolation to other locations

Models can be used to extrapolate results to other sites and climates over space and/or time. These could include potential sites where a particular system has not been practiced previously and the impact of climate change predictions on crop performance.

Timsina *et al.* (1998) calibrated and validated the CERES-Rice and Wheat models and established the long-term yield trends for rice-wheat systems at Nashipur in northern Bangladesh. Using the minimum soil, crop and weather data, they then predicted the long-term yield trends of

two rice (BR 14 and BR 11) and two wheat (Kanchan and Sowgat) cultivars for low (zero N, rainfed) and high (120 kg N ha⁻¹, irrigated) input systems for three sites in north (Dinajpur District), northwest (Jessore District) and central (Gazipur District) Bangladesh. Across sites, years, moisture and N regimes, BR 11 rice always out yielded BR 14, consistent with experimental results. Wheat yields across sites and years were highest at Nashipur due to lower minimum temperatures and higher solar radiation during the growing season. Conversely, yields were lowest at Gazipur due to higher temperatures and lower solar radiation. The results also indicated that without added N fertilizer, N will be limiting for both rainfed and irrigated rice-wheat systems in Bangladesh.

2.6.6. Impacts of climate change on yield

Both CERES-Rice and CERES-Wheat have been used to study the effect of global climate change on rice and wheat production worldwide. Climate change scenarios were generated either by changing the values of weather parameters (temperature, radiation, rainfall) and CO₂ concentration singly or in combination, or by General Circulation Models (GCMs) of which four were most commonly used - the Goddard Institute for Space Studies (GISS) model (Hansen *et al.*, 1983), the Geophysical Fluid Dynamics Laboratory (GFDL) model (Manabe and Wetherald, 1987), the United Kingdom Meteorological Office (UKMO) model (Mitchell *et al.*, 1989) and the Canadian Climate Centre (CCC) model (Wilson and Mitchell, 1987). The difference between 1×CO₂ and 2×CO₂ mean monthly GCM temperatures and the ratio of 2×CO₂ : 1×CO₂ monthly GCM precipitation totals were determined using the GCMs, where 1×CO₂ refers to current climate conditions and 2×CO₂ refers to the climate that would occur with a doubling of the CO₂ level. The daily weather data for use in

the crop models under climate change were adjusted based on the changes in the monthly means generated by the GCMs.

Bachelet *et al.* (1993) and Bachelet and Gray (1993) reviewed the three rice models (MACROS, CERES-Rice and RICESYS) to evaluate their suitability to assess the impact of global climate change for rice-growing areas in Asia. Grain yield response of both MACROS and CERES to temperature and CO₂ and of RICESYS to temperature, agreed well with the glasshouse experimental data. MACROS simulated a sharper decrease in potential yield than CERES, agreeing with experimental data of Baker *et al.* (1990a,b), but CERES predicted a lower impact of temperature change on potential rice yield than MACROS (18% and 62% yield decrease for an increase in temperature from 25°C to 30°C, respectively), consistent with the results of Baker *et al.* (1990b). CERES-Rice predicted a 15% increase in potential yield due to doubling of CO₂ concentration compared with a 9% using MACROS, both results well below the 47% increase observed by Baker *et al.* (1990b). In the Philippines, Singh and Ritchie (1993) studied the impact of climate change on crop growth and yield of IR 58, a heat-sensitive and an imaginary heat-tolerant cultivar, and the nutrient dynamics at IRRI, Los Banos, and at Munoz, Nueva Ecija. As temperature was increased by 0 to 5.5°C, growth duration was reduced by up to 10 d, reducing the potential yield of both cultivars. The reduction was, however, less for the heat tolerant cultivar. The simulated grain yields over the entire temperature range were markedly higher with a CO₂ concentration of 540 ppm. With the exception of the zero N treatment, grain yield of the heat-tolerant cultivar was always higher with enriched CO₂ concentration.

Baer *et al.* (1994) used CERES-Rice and Wheat with three climate change scenarios (GISS, GFDL, UKMO) to determine the potential impacts of climate change on rice and wheat production in Wangan Hills

(western Australia), Roseworthy (South Australia), Horsham (Victoria), and Griffith and Narrabri (NSW). The scenarios included: (a) baseline climate, (b) GCM climate change scenarios alone, (c) GCM climate change scenarios with 555 ppm CO₂, (d) sensitivity analysis where base daily temperature and precipitation were modified by fixed amounts and (e) changes in management to analyse adaptive strategies to climate changes (for example, planting dates and cultivars). In most sites, dry land wheat yields increased with rainfall increase and both dry land and irrigated yields generally decreased with increasing temperature, the latter due to the shortening of the growing season. Rice yields also decreased slightly under various climate change scenarios. The most effective adaptive strategy to climate change was from changing the cold-resistant rice cv. Calroseto a more tropical cv. IR-36. For wheat, by changing wheat sowing date from 30 May to 15 May to maximize water availability.

Escano and Buendia (1994) also studied the impact of climate change on rice yields in Batac and Los Banos in the Philippines. Projected climate change caused simulated rice yields to decrease at both locations, but the decreases were larger at Los Banos, which has lower latitude. The effects of increased temperatures and increased CO₂ concentration were similar to those reported by Singh and Ritchie (1993). Possible adaptation strategies included earlier planting and changing cultivars, which could however, bring major changes to the current farming systems in the Philippines.

Karim *et al.* (1994) studied the impact of climate change on rice production at two contrasting locations (Mymensingh and Barisal) in Bangladesh. At both sites, simulated rice yield decreased significantly with temperature increases but this was offset by the physiological effects of CO₂. The study concluded that if CO₂ concentrations did not increase, or if the fertilisation effects of CO₂ were less than predicted, then rice

production in Bangladesh could be negatively affected and the country's food security for the increasing population would be threatened from climate change.

Seino (1994, 1995) determined the impacts of climate change for various scenarios (GISS, GFDL and UKMO) for rice, wheat and maize in several locations in northern, central and South Western Japan. In southwestern Japan wheat is grown in rice fields in winter. Increasing temperature by 2 and 4°C reduced the growth duration of rice by 9 to 32 d and reduced yield by 9 to 22%. Decreased precipitation did not have any adverse effect on rice yield as most rice is fully irrigated in Japan. Increasing CO₂ concentration to 555 ppm increased rice yield by up to 20%. Increasing temperature increased irrigation requirement and increasing precipitation and CO₂ concentration reduced irrigation requirement. High temperatures shortened the growth duration of wheat by 8 to 30% and decreased ET by 5 to 9% and yield by 17 to 30% in northern Japan. The effect of high temperatures was a little less in southwestern Japan, reducing growth duration by 10 to 20%, ET by 3 to 4%, and yield by 7 to 15%. Increasing precipitation and CO₂ concentration increased the grain yield of wheat. While increasing CO₂ compensated for the effect of increasing temperature in central and northern Japan, it didn't compensate in southern Japan. Early planting, irrigation, and new cultivars adapted to climate change were considered to be possible adaptation strategies in both rice and wheat. In most cases in northern Japan, yields increased under climate change with earlier planting. However, in Kyushu in southern Japan, earlier planting did not improve yields due to high temperature stress and new cultivars better adapted to the new climate would be required.

Tongyai (1994) studied the impact of climate change on simulated rice production for four locations (ChiangMai, Phitsanulok, Nankhon

Sawan and Bangkok) in Thailand using CERES-Rice. Projected climate change caused yields (both upland and paddy rice) to decrease dramatically due to temperature increases. Yield decreases were partially counteracted by the physiological effects of increased CO₂. Despite differences among the GCM scenarios, locations and agricultural practices, rice yields under all climate change scenarios dramatically decreased in comparison with base-line yields.

Singh and Padilla (1995) studied the effect of climate change on rice yield and adaptive management practices in the Philippines in more detail. They reported that, under the current temperature regime, there would be beneficial effects of CO₂ enrichment from current (330 $\mu\text{mol mol}^{-1}$) to high (660 $\mu\text{mol mol}^{-1}$) concentrations in terms of increased grain yield, reduced transpiration, increased water-use efficiency, increased radiation use efficiency, reduced N losses and higher N-use efficiency. The trends would be reversed for all the above parameters for each °C increase in temperature from 0 to 5°C at each CO₂ level. The increase in grain yield with high N at 660 $\mu\text{mol mol}^{-1}$ concentrations was much greater than at 330 $\mu\text{mol mol}^{-1}$ concentration. At zero N, crop response to temperature was similar, but response to an increase in CO₂ concentration was very low, suggesting that the benefits of higher concentration would be more pronounced in high input irrigated rice. Further, some of the negative effects of temperature increase in warmer regions could be offset by the use of rice cultivars tolerant to high temperature-induced spikelet sterility and by planting cultivars with longer growth duration, particularly longer grain-filling duration.

Zhiqing *et al.* (1995) studied the effect of climate change on rice production in nine provinces in eastern, central-western and southern China. The studies compared baseline and doubled CO₂ climate change scenarios generated by GISS, GFDL and UKMO. They also considered the

physiological effects of CO₂ on rice growth for each scenario and examined several strategies for adapting to climate change. In both studies, simulated rainfed rice yields in all provinces decreased due to shortened growth duration as a result of increases in temperature and, at some provinces, due to sharp decreases in rainfall. Irrigation improved rice yield, especially in regions where rainfall decreased due to climate change. In rainfed rice, the direct effects of increased CO₂ concentration compensated for the negative effects of climate change in most sites, except where rainfall sharply decreased. In irrigated rice, rice yields increased in comparison with the baseline yields in the northern sites but decreased in the central and southern sites for all three GCM scenarios, suggesting that there is less compensation by the physiological effects of CO₂ in areas with high temperature. Under all climate change scenarios, the amount of water needed for irrigation increased greatly in areas where the rainfall decreased sharply, and evapotranspiration of rain fed rice was usually less than that for irrigated rice, suggesting that rain fed upland rice could be developed in areas where irrigation water was not available. Further, an increase in temperature would increase the area for rice cultivation as the northern limits for double rice and triple rice could be moved northward by about 5 to 100° of latitude. As a result the cropping index would increase and the cultivar and management (planting date, etc.) conditions would have to be adjusted to the new conditions.

Amien *et al.* (1996) also used three models (GISS, GFDL and UKMO) and generated several scenarios for Ngawi (East Java) and Sukamandi (West Java) in Indonesia. The models predicted that doubling greenhouse gases would increase solar radiation by 1.2 to 2.1%, minimum and maximum temperatures by 7.6 to 16.8% and rainfall by 20.5 to 91.7%.

CERES-Rice predicted that climate change could reduce rice yield by about 1% annually in East Java and slightly less in West Java.

In the Philippines, Buan *et al.* (1996) also used CERES-Rice v.3.0 in combination with results from four GCMs (CCCM, GFDL, UKMO and GISS) to assess the impact of climate change on two rice (IR-64 and IR-72) cultivars. The first three scenarios generally increased yields, but the GISS scenario decreased yields. Decreased rice yields were partly due to a decrease in the grain-filling period as a result of increased CO₂ concentration resulting from increased day and night temperatures, but was also partly due to increased flooding that would be brought about by a 10% increase in rainfall. CERES-Rice was unable to simulate the effects of strong winds that would result from typhoons.

Timsina *et al.* (1997) analyzed the effect of climate change for 12 scenarios (effect of temperature, CO₂, solar radiation separately and in their various combinations) on grain yields and phenology of rice, wheat and maize for several locations in the hills and terai of Nepal. There were significant effects of climate change on the yield and phenology of all crops. Temperature had the greatest effect. Increasing temperature shortened growth duration, decreasing grain and biomass yields, while decreasing temperature increased duration and grain yield. Increased solar radiation or CO₂ increased yield without affecting growth duration. The increased temperatures had less negative effect on rice than on the other two crops. As has been observed in many other studies, the positive effects of increased CO₂ were offset, to varying extents, by the negative effects of higher temperatures and increased rainfall. There were interactions between weather variables for both rice and wheat. The effects of climate change were different for different cultivars and sites. The main conclusion was that the major negative effect of climate change on yields in Nepal was due to temperature increases, not rainfall changes.

Hundal *et al.* (1998) also studied the effect of climate change on the yields of rice cv. PR 106 under various scenarios in Ludhiana. Increased temperature advanced wheat maturity, but delayed rice and reduced leaf area, biomass and yield more in wheat than in rice. A 10% decrease in radiation decreased the maximum LAI by 7.6% in wheat and 5.9% in rice, whilst a 10% increased LAI by 7.1 and 5.7%, respectively. Both biomass and grain yields of rice and wheat increased with increased solar radiation. Increasing CO₂ concentration to 600 ppm increased LAI, biomass, and grain yield of rice by 11, 7.7, and 8.7%, respectively. Decreased rainfall did not have any effect on rice and wheat yields as those crops were fully irrigated. The interaction between temperature and solar radiation didn't have any effect on phenology. Negative effects on LAI, growth and yield of wheat were further intensified where both temperature and radiation were increased. In rice, however, the adverse effect of an increase in temperature by 1°C on growth and yield was compensated for by increasing radiation by 5%. Increasing both temperature and CO₂ concentration reduced the maximum LAI, biomass and grain yield of rice.

Lal *et al.* (1998) predicted rice and wheat yields for various climate change scenarios (increase or decrease of maximum and minimum temperatures, CO₂ concentrations and various water management levels) for Delhi, Hissar and Ludhiana. Greater yields of both crops (15 and 28%, respectively) were predicted for doubling of CO₂ levels, but this was nearly cancelled out by 3 and 2°C temperature rises during the wheat and rice seasons, respectively. While wheat yield was decreased by an increase in maximum temperature, rice was affected by an increase in minimum temperature. With increasing CO₂ and maximum and minimum temperatures, wheat yields would increase by 21% while rice yields would increase by 4%.

Saseendran *et al.* (2000) analysed the effect of climate change on rice productivity at five sites in Kerala, India. Changes in temperature ranged from -5 to +5°C with an increment of 1°C over the observed baseline climate data. Changes in rainfall ranged from -16 mm/d to 16 mm/d with an increment of 2 mm/d added to each rainy day. CO₂ levels ranged from 180 ppm to 1230 ppm. Across Kerala, an increase in CO₂ concentration led to a yield increase and enhanced water-use efficiency. Yield declined by about 6% for every degree increment in temperature up to 5°C. The physiological effect of ambient CO₂ at 425 ppm compensated for the yield losses due to increase in temperature of up to 2°C. There was a near exponential increase in rice yield for an increase in rainfall above observed values, but there was yield loss of about 8% for a decrease in rainfall by 2 mm/d.

Aggarwal and Mall (2002) also predicted the impact of climate change under various scenarios (no change in weather, gradual change in CO₂ from 350 to 750 ppm in steps of 50 ppm, and temperature from 0 to 5°C in steps of 1°C, and interaction effects of different levels of CO₂ and temperature) on rice yield in Delhi, Patna, Puna and Coimbatore. Rice yields increased by 1.0 to 16.8% in optimistic scenarios (low increase in temperature and high increase in CO₂) and decreased by 3.5 to 33.8% in pessimistic scenarios (low increase in CO₂ and high increase in temperature).

2.6.7. Aiding government policy and strategic planning

CERES models have also been used to estimate national food production and thus aid government policymakers. For example, in 1991-92 there was an unexpected shortfall in the size of its winter wheat harvest in Albania and USAID wanted to determine to what extent wheat imports might be offset with emergency N fertilizer imports. CERES-Wheat was then used to test the effect of a single N top-dressing applied

at different times during the spring, the results of which the USAID was able to use to evaluate the potential benefit of imported N and the importance of timing applications. They decided that it was worth it, and it marked the beginning of a substantial aid package to Albania for improving fertilizer markets and availability in the country (Bowen and Papajorgji, 1992).

Chou and Chen (1995) documented that combined use of satellite imagery, GIS and CERES-Rice was useful for mapping potential land productivity and suitability under irrigation in Taiwan. In Java, Indonesia, there is a concern that rice self-sufficiency, maintained since 1984, could be threatened by climate change.

Amien *et al.* (1996) used three models including CERES-Rice to simulate the effect of climate change to aid policy makers in planning for the effects of recurring droughts and other possible changes on national food production. The simulations suggested that climate change could reduce rice yields by an annual average of about 1% in East Java and less in West Java due to an increased incidence of drought.

Aggarwal *et al.* (2000b) also used several models including CERES-Rice and Maize to determine potential crop yields with and without constraints including water, N, capital, labour, farmer's income and options to maximize food production and farmers' of regional incomes for the State of Haryana, India.

2.7. Calibration of crop simulation models

Model calibration or parameterization is the adjustment of parameters so that simulated values compare well with observed values. The genetic coefficients that influence the occurrence of developmental stages in the CERES models can be derived iteratively, by manipulating the relevant coefficients to achieve the best possible match between the simulated and observed number of days to the phenological events. Other

coefficients can be derived from determinations of non-limited grain weight, number of grains per panicle (rice) and rate of grain filling (wheat). Alternatively, genetic coefficients can be determined using the GENCALC software that uses the observations of phenological events from one or several experiments from a range of environments (Hunt and Pararajasingham, 1994).

The DSSAT shell includes default genetic coefficients for a range of species and cultivars. The model user can also develop estimated coefficients for local conditions from the default coefficients. Many commonly grown cultivars are not included in the DSSAT shell, many of the cultivars that are included are not commonly grown and the source of the genetic coefficients is not provided. The DSSAT shell contains genetic coefficients for very few varieties of rice and wheat grown in rice-wheat areas of Asia and Australia. Generally, data sets collected from previous agronomic research are lacking in some of the key observations required for calibrating process-based crop growth models.

CERES-Rice has been widely evaluated and used across Asia and Australia, however most studies do not describe how the genetic coefficients were derived nor the values used. Moreover, many reports do not even provide the cultivar names or the observed number of days to phenological events, making it difficult to calculate or assign coefficients. Many studies do not report the version of CERES-Rice used. The coefficients for RR-21 derived from separate studies in India and Nepal were very similar (Timsina *et al.* 1995, 1997), but there were differences in the values of coefficients for HD-2329 derived by Hundal and Kaur (1997) and Pathak *et al.* (2003) using CERES-Wheat v.2.0 and v.3.5, respectively. One reason for the differences could be due to the use of different versions of CERES-Wheat. As for rice, most of reported genetic

coefficients are derived from results of a single site, soil, and weather conditions (Timsina and Humphreys, 2003).

Villalobos and Retana (1998) calibrated the CERES-Rice model with data from the Liberia region of Costa Rica and validated it by a statistical analysis comparing actual and simulated rice yields for the region. There was an index of agreement of 92%, a correlation coefficient of 92% and a determination coefficient of 84%.

Casanova *et al.* (2000) calibrated phenological development, daily dry matter production and leaf area development and validated the ORYZA1 with field data for a short-grain (cv. Tebre) and a long-grain rice cultivar (L-202). They reported that there were no significant differences between the cultivars for the total length of the growth period. However, the pre-heading period was longer and the post-heading period shorter in L-202 than in Tebre. This resulted in differences in translocation characteristics, spikelet number per unit area, weight of the grains and harvest index. The following crop characteristics were similar in both the two cultivars: extinction coefficient, dynamics of nitrogen distribution, partitioning of assimilates, relative death rate of leaves, relative growth rate of leaf area during exponential growth, specific leaf area and specific stem green area.

The simulated curve fitted the observations much better when leaf area index was considered as comprising the leaf blade area only, without a photosynthetic contribution by the stem green area. The model simulated rice growth very accurately until flowering. After flowering, however, divergences appeared and increased especially at the yellow ripe stage. From then on the crop did not grow much more, whereas it continued in the simulation. This reduction of growth rate was usually accompanied by an increase in the relative death rate of leaves and the drying of the grains. The main source of error may be a limited

understanding of the ripening and sink limitation processes. A considerable yield gap between potential and observed yield remained. A climatic variability assessment over 10 years from 1987 to 1996, showed a small but correlated variation in both simulated and measured rice yields.

Yao *et al.* (2005) used a set of data from 129 experiments conducted from 1981-2000 in different locations in China as inputs for the CERES-Rice model. They have selected 19 experiments on the effects of nitrogen management, sowing dates, cultivars and seasons on rice yield from the 129 experiments. They reported that the flowering duration in the data sets varied from 77 to 135 days, whereas the yields ranged from 3104 to 11448 kg ha⁻¹. They have selected a separate group of 28 experiments for the calibration of the model and for calculating genetic coefficients. The genetic coefficients of different cultivars used for validating the model were estimated by repeatedly adjusting the model until a close match between the simulated and the observed phenology and yield was obtained. They observed that the the simulation of yield by CERES-Rice model is in agreement with the observed yields and the error values lie between the simulated and observed yields.

Li *et al.* (2005) calibrated and validated ORYZA2000 model for its simulation of aerobic rice growth. They reported that the values of aerobic biomass, yield and N uptake simulated by ORYZA2000 were significantly linear with the observed values, which showed a better simulation effect. However, the simulation of soil water potential was not good enough, and more research was needed. They have determined the optimum economic application and amount of N fertilizer under different irrigations and density management for aerobic rice on the basis of the results of calibration and evaluation.

2.8. Evaluation of crop growth simulation modeling

Validation is the comparison of the results of model simulations with observations from crops that were not used for the calibration. A model should be rigorously validated under widely differing environmental conditions to evaluate the performance of major processes in addition to its ability to predict yield. CERES-Rice has been validated and evaluated for many locations across the rice-growing regions in Asia and Australia.

Before any model can be used with confidence, adequate validation or assessment of the magnitude of the errors that may result from their use should be carried out. Model validation, in its simplest form, is a comparison between simulated and observed values. Beyond comparisons, there are several statistical measures available to evaluate the association between predicted and observed values. Test criteria have been separated into two groups, called summary measures and difference measures. Summary measures include the mean of observed values ($\bar{o}$) and predicted values ($\bar{P}$), while the standard deviations of observations (S_o) and predictions (S_p), the slope (a) and intercept (b) of the least square regression are the examples of difference measures.

Calibration of any model is needed for each and every variety of crop for adjusting certain model parameters or relationships to make the model work for study sites. On the other hand, validation determines that the model works in totality with independent data sets for comparison. Validation of model shows how well a model performs in a particular set of circumstances.

2.8.1. Phenology

The ability of CERES-Rice to predict the duration of key phenological events has been examined in many studies. In tropical Asia, validation of CERES-Rice was first reported by Alocilja and Ritchie (1991)

for three upland rice cultivars (IR 43, UPLRi 5, UPLRi 7) in six experiments in the Philippines. Agreement between observed and predicted values of days to physiological maturity was good, with differences of only 0 to 4 days at three sites in Bangkok, Thailand. Tongyai (1994) reported that the simulated number of days to physiological maturity was overestimated by 8 to 16 days.

Jintrawat (1995) evaluated CERES-Rice (v.2.0) for both photoperiod sensitive and insensitive cultivars against two years of data for six sites in north and north east Thailand. He found accurate model predictions of phenology for photoperiod insensitive cultivars, but for a photoperiod sensitive cultivar the heading dates were underestimated, especially for early planting dates. The author attributed this primarily to N shortage, but more importantly, it was due to the inability of v.2.0 of the model to simulate the growth and phenology of photoperiod sensitive cultivars. The ability to simulate growth and phenology of photoperiod sensitive cultivars is included in more recent versions of CERES-Rice.

Using data sets from several experiments at Pantnagar, North West India, Timsina *et al.* (1995) found that CERES-Rice predicted the number of days to anthesis of Pant-4 cultivar to within four days for 4 out of 10 treatments, while predictions were underestimated by 5 to 14 days in 6 treatments. The number of days to maturity was within 4 days in 4 out of 12 treatments and over or under-estimated by 5 to 14 days for 8 treatments. In Kerala, south India, the predictions were better with simulated anthesis dates of Jaya and IR 48 within 4 days and maturity dates within 2 days of observed dates (Saseendran *et al.*, 1998a, b).

Timsina *et al.* (1998) reported almost perfect agreement between the predicted and observed number of days to maturity of BR-11 and BR-14, although the predicted number of days to anthesis was 4 to 7 d earlier than the observed number of days. Seino (1995) predicted number of days

to physiological maturity of unspecified cultivars was within -2.8 to +2.1 d of observations at temperate and sub-tropical climate locations in northern and South Western Japan.

The ability of CERES-Rice to predict phenology has also been compared with other models. For example, Mall and Aggarwal (2002) compared the performance of CERES-Rice and ORYZA1N and reported that both models predicted the number of days to flowering reasonably well for 11 locations from north to south India, including four locations in northwest India (Delhi, Pantnagar, Ludhiana and Kapurthala). The observed duration from sowing to flowering varied from 37 (Coimbatore) to 85 (Pantnagar) days whereas the simulated duration varied from 36 (Coimbatore) to 85 (Pantnagar) days for CERES-Rice and 43 (Coimbatore) to 78 (Pantnagar) days for ORYZA1N. Most of the simulated values were within 15% of observations for both models, but CERES-Rice simulated flowering duration with less error (RMSE= 4.5 d) than ORYZA1N (RMSE= 4.8 d).

Tongyain (1994) reported reasonable agreement between simulated and observed days to anthesis and to maturity (RMSE = 4.8 d and SE = 4.4 and 4.6 d, respectively, for anthesis and maturity) for a range of varieties across tropical, sub-tropical and temperate environments for the evaluation of CERES-Rice to predict the number of days to anthesis and maturity in Thailand which used photoperiod sensitive varieties with CERES v.2.

Salam *et al.* (2003) compared observed and predicted values for six rice growth models (CERES-Rice, ORYZA1, ORYZA-European, RICAM, SIMRIW and TRYM) in four diverse rice-growing environments in Asia (early and late sowing at Nan Chang, southern China; Moroika, northern Japan; and dry season at Los Banos, Philippines), for 10 years of observations at each site. Model predictions for four traits (growth

duration, grain yield, above ground biomass and harvest index) were compared with observations using mean squared deviation (MSD) and its three additive components. Across the four data sets and 10 years, the MSD for growth duration ranged from 87 to 238. CERES-Rice, RICAM, SIMRIW and TRYM had the smallest MSDs. All models simulated the growth duration well at Nan Chang for early and late sowing, whereas the simulated duration deviated more for Moroika and Los Banos.

2.8.2. Grain and biomass yields and yield components

Validation of CERES-Rice for grain and straw yields and yield components has been reported for several field studies across Asia. The first report was by Godwin *et al.* (1990), who compared the predicted grain and biomass yields against data from field experiments at several sites in the Philippines (Buresh *et al.*, 1988a,b John *et al.*, 1989a,b). In most cases, there was a good agreement between predicted and observed values, with R^2 of 0.65 and 0.67, respectively, for grain and biomass yields. Although, as discussed above, CERES-Rice did not always accurately predict the date of phenological events in Thailand, it predicted grain yield quite well. For example, Tongyai (1994) reported a fairly good agreement between simulated and observed grain and biomass yields for 3 sites over 3 years in Bangkok. Grain yields were overestimated by 0.2 to 0.4 t ha⁻¹ (4.5 to 9%) and biomass was underestimated by 0.8 to 1.0 t ha⁻¹ (10 to 12%). In central, north and northeast Thailand, CERES-Rice predicted grain weight, grain number, and grain yield of both photoperiod sensitive and insensitive cultivars reasonably well (Jintrawat, 1995). Grain weight was predicted within 0-3%, grain number m⁻² within 15 to 50% and grain yield within 15 to 20% of observed values.

Kropff *et al.* (1994) compared predicted yield potential for four rice models (ORYZA1, CERES-Rice, SIMRIW and TRYM) in four

environments (dry and wet season crops at IRRI/Philippines, Kyoto/Japan, and Yanco/Australia). All models simulated the wide range in total biomass accumulation and yield relatively accurately. However, all models overestimated yield in the wet season at IRRI and with the exception of ORYZA1, all models predicted LAI inaccurately.

Seino (1995) compared the simulated and measured grain yields for three sites (Miyagi and Niigata in the north and Miyazaki in the south) in temperate Japan. At all sites, simulated grain yields were within 0 to 5% of observed yields. In temperate southern Australia, predicted yield of Amaroo grown in 1989/90 was within 10% of the measured yield of 9.6 t ha⁻¹ however, there were large discrepancies between the yields of experiments from other years and yields simulated by CERES-Rice v.2.1 due to sterility induced by cold damage, which is not simulated in official versions of CERES-Rice.

Timsina *et al.* (1995) reported that the simulated grain yields of Pant-4 were generally within 1 to 15% of observed yields for many experiments at Pantnagar in North West India. But in some cases, the simulated yields were out by up to 40%, mainly due to the fact that the model didn't accurately predict the phenological events. In northern Bangladesh, simulated yields of BR-14 and BR-11 were either over or underestimated relative to observed yields, which was reflected in the high RMSE of 1.3 t ha⁻¹. The model undoubtedly underestimated yields at zero N (Timsina *et al.*, 1998). However, some of the discrepancy between simulated and observed yields was due to insect damage and lodging at high N rates, which resulted in lower yields.

In Indonesia, Amien *et al.* (1996) reported that CERES-Rice (v.3.0) under predicted grain weight by 1 mg resulting in under prediction of yields by 10 to 20% at all locations, except Sukamandi in west Java. Observed grain yields across locations ranged from 2.65 t ha⁻¹ to 7.85 t ha⁻¹.

¹while the simulated yields ranged from 2.65 to 7.0 t ha⁻¹, with R² of 0.87. In East Java, they reported a grain yield of 5.1 t ha⁻¹ with 250 kg of urea/ha compared with 5.8 t ha⁻¹ from the simulation. Using MERES, Mathews *et al.* (2000) reported good agreements between simulated and observed grain yields at Los Banos, Philippines and Hangzhou, China, except for three treatments in the dry season at IRRI with mid-season drainage.

In the sub-tropical environment of Kerala, Saseendran *et al.* (1998a,b) reported that grain yields of Jaya and IR-8 were within 3% and straw yields within 27% of measured yields, and that grain weight and grain number m⁻² were also predicted closely. In the same state, Rao *et al.* (2002) also observed very good agreement between simulated and observed yields of Jaya, Jyothi, and Triveni for all transplanting dates in one year (0 to 2% of observed values). In a year in which heavy rains which caused high sterility, the simulated yields were 5 to 10% greater than the observed yields. Boonjung (2000) also reported good agreement between observed and predicted yields of the photoperiod sensitive cultivar KDML (R²= 0.70) in the northeast Thailand.

Mall and Aggarwal (2002) concluded that both CERES-Rice and ORYZA1N predicted grain yield satisfactorily (within $\pm 15\%$), especially for yields above 4 t ha⁻¹. The accuracy of prediction of grain and biomass yields was similar for ORYZA1N (RMSE=0.6 t ha⁻¹) and CERES-Rice (RMSE=0.7 t ha⁻¹). Both models also predicted grain number fairly accurately over the range 15,000 to 32,000 grains m⁻². The authors concluded that both models were unable to adequately simulate crop growth and yield when there are stresses such as low N and water deficit. At lower yield levels, ORYZA1N performed better than CERES-Rice, whereas the reverse was true at higher yields.

Salam *et al.* (2003) found that CERES-Rice, ORYZA1, ORYZA-European, RICAM, SIMRIW and TRYM all closely predicted the Moroika

and Nan Chang early sowing yields, but gave large deviations for late sowing at Nan Chang and the dry season at Los Banos. The largest deviations occurred with SIMRIW and ORYZA1, followed in order by TRYM, CERES-Rice, ORYZA-European and RICAM. CERES-Rice and RICAM had the highest and lowest deviations for biomass, respectively. Although the difference between models was much less than for grain yield. For harvest index, the largest deviation was from RICAM and the smallest with TRYM. RICAM and ORYZA1 had the largest MSD for Nan Chang early and late seasons, while CERES-Rice had the largest MSD in Moroika. The results show that agreement between observed and predicted yields and final biomass was not very satisfactory (RMSE=1.55 and 13.1 t ha⁻¹, SE=1.44 and 2.94 t ha⁻¹, and R²=0.38 and 0.25 respectively, for grain and biomass yields), suggesting that growth and biomass routines need to be revisited and refined, and/or deficiencies in the data sets.

2.8.3. Growth

There are only a few published reports on the performance of CERES-Rice in predicting the time course production of biomass and leaf area. Using MERES, Mathews *et al.* (2000) found good agreement between observed and predicted total above and below-ground biomass in the Philippines and China for all treatments except those with mid season drainage.

Salam *et al.* (2001) developed nursery growth and transplanting shock routines using data from Bangladesh and incorporated them into CERES-Rice. Without the new routine the model overestimated root and leaf dry matter and underestimated culm dry matter during the 30-d period of seedling growth and overestimated the duration of the period of transplanting shock. With the new routine, the seedling growth and

transplanting shock periods were simulated well. However, the response to transplanting shock was not simulated well.

Mall and Aggarwal (2002) concluded that there was a good agreement between the measured and simulated values (using CERES-Rice and ORYZA1N) for the general pattern of LAI over the growing season, however both models under predicted peak LAI and the authors attributed this to limited calibration and initialization of the models. CERES-Rice simulated LAI at different growth stages slightly better than the ORYZA1N in all treatments. Meyer *et al.* (1994) also observed that CERES-Rice v.2.1 underestimated peak LAI considerably, although it predicted the time of complete canopy closer (LAI ~3) reasonably accurately. The predicted panicle density was also greatly under-predicted.

2.9. Sensitivity study of the crop simulation models

A major issue with simulation modeling is the large number of model parameters (calibration values) and input data that are required. The question naturally arises: what happens if we get some of these wrong? The correct question is: how sensitive is the model to variations in parameters or data? Especially since parameter calibration is largely a black art, sensitivity analysis allows us to see where we should concentrate our calibration and modelling efforts, i.e., where the model is most sensitive. Sensitivity means rate of change in output variable per unit change in input variable or parameter. Sensitivity study of crop simulation modeling involves exploring the behaviour of the model for different values of parameters.

Aggarwal *et al.* (1996) studied crop simulation model ORYZA1 to identify useful physiological traits of a plant type for potential yield. The study indicated that the relative importance of different physiological traits might change with season and a 20 % change in any one individual

trait could provide only a small increase in yield potential. However, simultaneous changes in leaf area, leaf N content, spikelet number, potential grain weight and grain filling duration estimated grain yield which were consistently higher than those estimated at 10 t ha⁻¹ over a 32 year period in the dry season of Philippines.

Lal *et al.* (1998) studied the possible impact of climate change on wheat and rice yields in North West India using CERES group of model. They found that the models predicted higher yields for both wheat and rice under elevated CO₂ levels, but a 2°C rise in temperatures was observed to have eliminated the positive effects of elevated CO₂ on wheat and rice yields.

Pathak *et al.* (2003) studied trends of climatic potential yields and on farm yields of wheat and rice in the Indo-Gangetic Plains using DSSAT model (CERES-Wheat and CERES-Rice). They also carried out sensitivity test of the models for radiation and temperature. Their results showed that solar radiation decrease by 1.7 MJ m⁻² day⁻¹ reduced rice and wheat yields from 10.9 to 10.3 and 8.3 to 7.5 Kg ha⁻¹, respectively. Increased minimum temperature by 1.7°C decreased yields of rice and wheat from 10.9 to 10.0 and 8.3 to 8.1 Kg ha⁻¹, respectively.

Materials and Methods

III. MATERIALS AND METHODS

The field experiments were conducted during *kharif* seasons of 2007 and 2008 at experimental field of Main Rice Research Station (MRRS), Nawagam, Anand Agricultural University, Anand (Gujarat), India to study the “Simulation of environmental and varietal effects on growth and yield of aromatic rice using CERES-Rice model in middle Gujarat Agro-climatic region.” The experimental details and the methodology used are described in this chapter.

3.1. Experimental site

The field experiments were conducted for two consecutive years during the *kharif* seasons of 2007 and 2008 at experimental field of Main Rice Research Station (MRRS), Nawagam, AAU, Anand (Gujarat), India. The farm is located at 22°48'N latitude, 71°43'E longitudes and at an altitude of 32.4 m above the mean sea level. The soil of the station and its surroundings is medium black deep to very deep, poorly drained and salt affected. The textural class of soil was Silty Loam having 38.1 % sand, 44.1 % silt and 20.8 % clay.

3.2. Climate

The location of the field experiment at the research farm falls under middle Gujarat Agro-climatic Zone -III of the Gujarat State. The climatic conditions of the area represents the subtropical conditions with semi arid climate. The Annual rainfall of this region ranges from 293 mm to 1658 mm with an average precipitation of 870 mm and is received through Southwest monsoon wind currents during the 3rd week of June to the 2nd week of September. The July & August are the month of heavy rains. The weather remains dry from October to June. The winter is medium cool and dry. While, summer is quite dry and hot. The January is the coolest month of winter with mean monthly minimum temperature varying from 9.4°C to 29.6°C on the other hand May is the hottest month in which the maximum temperature varies from 21.0°C to 43.3°C.

3.3. Microclimatic conditions prevailed during crop periods

In order to expose the growth and development of paddy crop to different sets of microclimatic conditions the crop was transplanted on three different dates, viz., first date of transplanting (D₁)- 8th July, second date of transplanting (D₂)- 22nd July and third date of transplanting (D₃)- 8th August. Climatic and microclimatic conditions prevailed under D₁, D₂ and D₃ have been illustrated through Fig. 3.1 and Fig. 3.2 for 2007 and 2008, respectively.

3.4. Meteorological observations

The Agrometeorological observatory is situated on the Main Rice Research Farm and is nearly 15 m away from the experimental site. All the weather parameters (temperature, rainfall, sunshine, evaporation, wind speed and direction and soil temperature) are recorded twice daily at 0738 and 1438 hrs (IST) were processed, analysed and used for the present investigation. Daily values of incoming solar radiation were computed from observed value of bright sunshine hours using solar radiation calculator (Glarner, 2006) which uses following formula.

$$QI = 1.974 * N (0.25 + 0.5 n/N)$$

Where

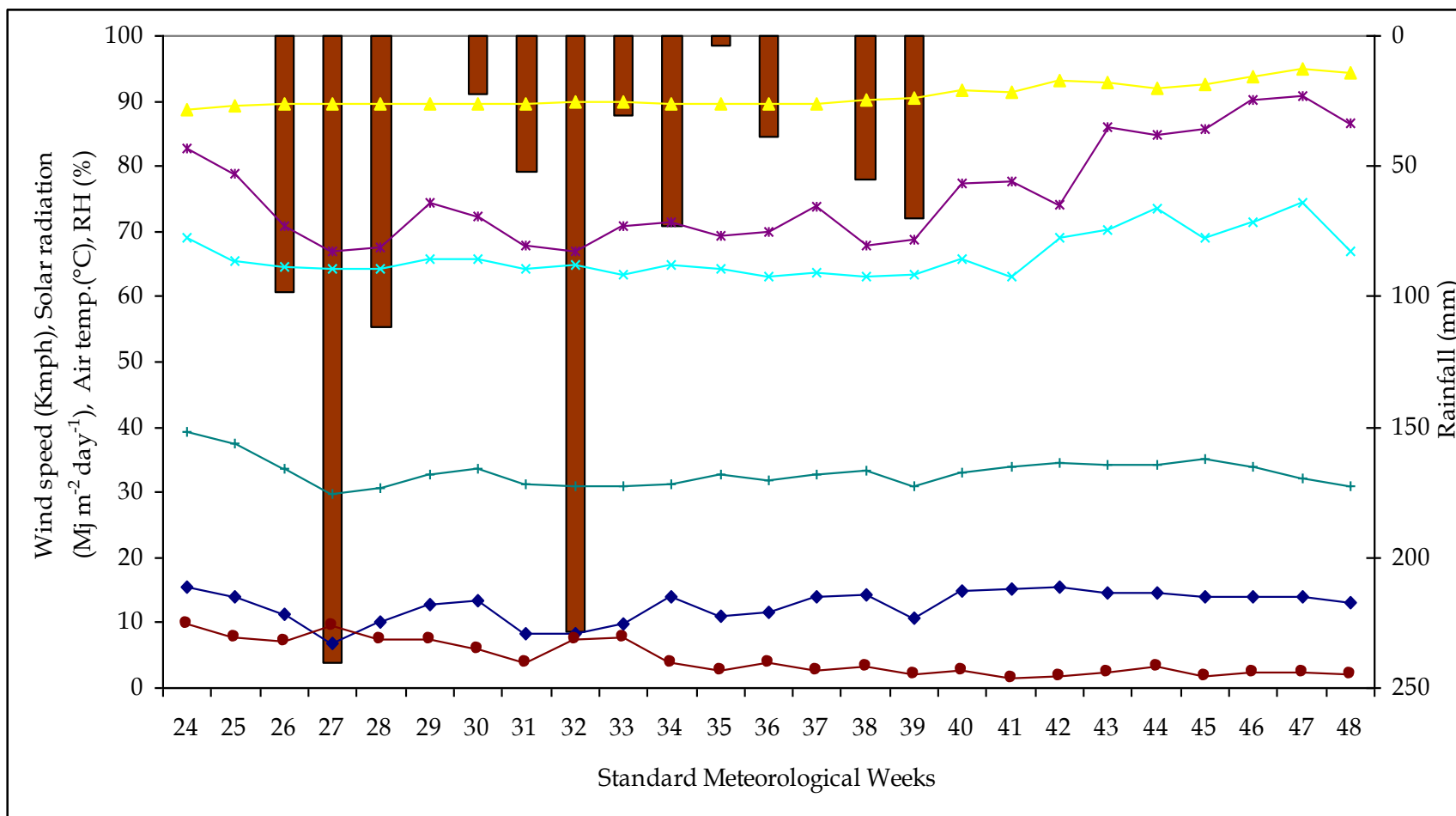
QI = incoming solar radiation at a place (MJ m⁻² day⁻¹)

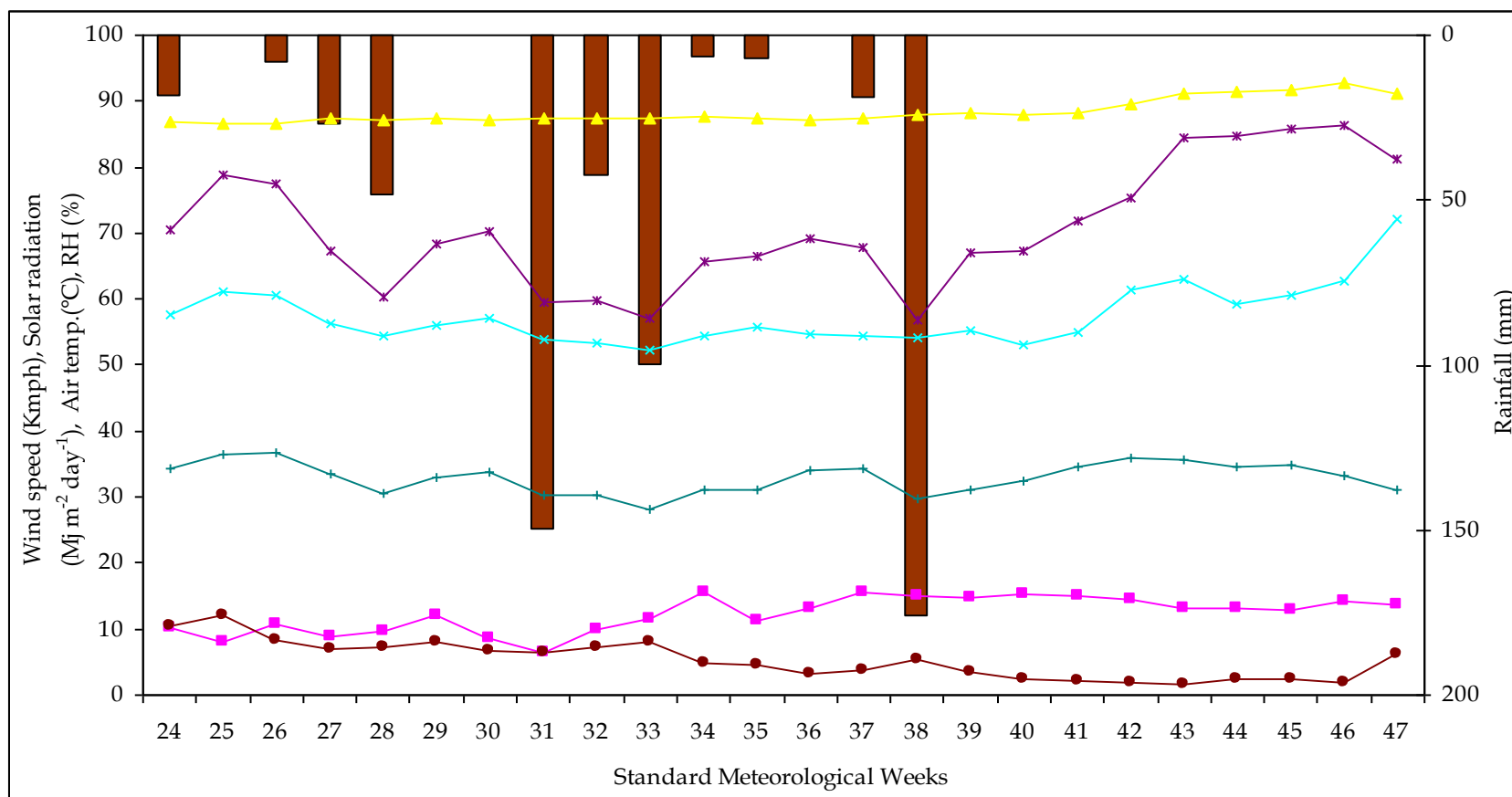
n = bright sunshine duration (hours)

N = maximum possible sunshine duration of a place (hours)

3.5. Description of soil of experimental field

The soil of the experimental site is representative of the soils of the region. These soils are of alluvial origin and are classified as “Silty Loam” and belong to Vertic Haplusteps type. The soil depth of experimental field was 180 cm and had a moderate to well drainage, water depth was more than 10 m, very slow erosion, very slow runoff, slope gradient was 0-1 %, physiographic unit was plain, flat type topography land form and no





flooding. The composite soil samples drawn from different depths before transplanting were analysed for physico-chemical properties of the soil. The physical properties of soil were determined using the standard methods. Bulk density of undisturbed soil was determined using the core sampler (Piper, 1966). To know the texture of the soil mechanical analysis was done using Bouyoucos hydrometer method (Bouyoucos, 1943). To know the available soil moisture storage capacity, field capacity and wilting point of the soil, pressure plate apparatus was used.

Table 3.1: Mechanical composition of soil of the experimental field (International pipette method, Piper, 1966)

Sr. No.	Sampling depth in cm	Particles Per centage			
		Sand	Silt	Clay	Textural class
1	0-15	38.1	44.1	20.8	Silty Loam
2	15-30	43.7	32.5	20.8	Silty Loam
3	30-60	38.6	31.2	30.2	Silty Clay Loam
4	60-90	30.5	40.7	28.8	Silty Clay Loam

The details of the mechanical composition of soil of the experimental field are presented in Table 3.1 and Physico-chemical properties in Table 3.2.

Table 3.2: Physico-chemical properties of soil of the experimental field

Sr. No.	Parameter	Sampling depth in cm			
		0-15	15-30	30-60	60-90
1.	Lower limit of moisture content (cm ³ /cm ³)	0.106	0.106	0.107	0.108
2.	Upper limit of moisture content (cm ³ /cm ³)	0.262	0.262	0.262	0.261
3.	Saturated moisture content (cm ³ /cm ³)	0.462	0.462	0.462	0.461
4.	Bulk density (g cm ⁻³)	1.69	1.73	1.79	1.85

5	EC (ds/m) (in 1:2 soil: water extract)	0.69	0.43	0.50	0.27
6	pH in 1:2 soil: water extract	8.3	8.0	8.1	8.1
7	C.E.C. (Meq/100gm)	10.2	13.9	16.9	24.5
8	Exchangeable Na ⁺ (Meq/100gm)	1.07	1.87	2.0	2.08
9	Exchangeable K ⁺ (Meq/100gm)	0.36	0.44	0.46	0.49
10	E.S.P (%)	10.49	13.95	11.83	8.48
11.	CaCO ₃ (%)	2.5	2.5	2.5	2.5
12.	Organic Matter (%)	0.78	0.57	0.52	0.43
13	Organic carbon (%)	0.45	0.33	0.30	0.25
14	Total N (%)	0.039	0.028	0.026	0.022
15.	Nitrate nitrogen (NO ₃)(µgN/g soil)	3.30	3.20	2.80	2.10
16	Ammonical nitrogen (NH ₄ ⁺) (µgN/g soil)	0.50	0.50	0.20	0.20
17	Available P ₂ O ₅ (kg ha ⁻¹)	18.59	17.75	13.52	10.14
18	Available K ₂ O (kg ha ⁻¹)	510.6	477.3	460.6	416.2

The chemical analysis of soil showed that the soil of experimental field was slightly alkaline in reaction, low in organic carbon, low in available nitrogen, medium in available phosphorous and high in available potassium.

3.6. Crop and cultivar

The important characteristic features of the four different cultivars of aromatic rice which were grown for the present investigation have been described in the Table 3.3.

Table: 3.3: Description of the cultivars grown

Cultivars	Parentage and Important Characters
Pankhali (P 203)	i. Breeding method used -Developed through selection of local variety grown in Nawagam area and released by released proposal, Main Rice research Station, Nawagam in 1955. ii. Plant is tall type, long extra glumes are present. iii. Rice grains are white, medium and scented. iv. Highly susceptible to blast. v. Suitable for <i>kharif</i> (transplanted type) seasons. vi. Test weight (1000 seeds) is 17.3 g. vii. Potential yield is 3000 to 3500 kg ha⁻¹ viii. Maturity days are 135-140 days. ix. Recommended for cultivation in Gujarat.
Narmada (Ambica)	i. Parentage- T (N) X Bas-370 ii. Breeding method used - developed through hybridization and selection and released by released proposal, Main Rice research Station, Nawagam in 1991. iii. Plant height is 110-125 cm; Plant is erect, open, tall and non lodging type. Foliage is green with strong culm, well exerted, compact type. Panicle is 27-29 cm in length and 8-10 in number. Awnless spikelet and extra glume is absent, long and slender grains. iv. Resistant to blast, grain discolouration and moderately resistant to narrow brown spot. Moderate resistant to leaf folder and White backed plant hopper and resistant to rice skipper and stem borer. v. Test weight is 19.4 g. Average yield is 4000- 5000 kg ha⁻¹. Viii. Maturity days are 140 - 145 days. ix. Recommended for cultivation in Gujarat.

GR- 104	i. Parentage –GR-101 X Basmati 370. ii. Breeding method used - developed through hybridization and selection and released by released proposal, Main Rice research Station, Nawagam in 2003. iii. Plant height is 120-130 cm, Plant is erect, open, tall and non lodging type. Foliage is green with strong culm, well exerted, compact type. Panicle is 27-29 cm in length and 8-10 in number. Awnless spikelet and no extra glume. Fine, long slender grains, good cooking quality with strong aroma. iv. Resistant to leaf and neck blast, resistant to moderate resistant to bacterial leaf blight, moderate resistant against white backed plant hopper and leaf folder. v. Suitable for <i>kharif</i> and summer season. vi. Test weight is 18-20 g. vii. Average yield is 4000- 5000 kg ha⁻¹. viii. Maturity days-135-140 days. ix. Recommended for cultivation in Gujarat.
Pusa Basmati	i. Parentage – Pusa 150 X Karnal local. ii. Breeding method used – developed through introduction and released by Rice section, department of Plant breeding and Genetics, Punjab Agricultural University, Ludhiana in 1990. iii. Plant height 100 cm, semi dwarf basmati variety. 110 days to heading. iv. Maturity -140 days v. Average yield is 4000 kg ha⁻¹. vi. Recommended for cultivation in Punjab.

3.7. Experimental details

Crop	Rice
Variety (Four)	V ₁ = Pankhali (P 203) V ₂ = Narmada (Ambica) V ₃ = GR- 104 V ₄ = Pusa Basmati-1
No. of treatments	Twelve (4 x 3)
Dates of transplanting (Three)	D ₁ : 8 th July D ₂ : 22 nd July D ₃ : 8 th August
Number of replication	Single replicate
Plot size	Gross: 4.5 m x 12.5 m Net: 4.00 m x 12.0 m
Spacing	20 cm X 10 cm

3.8. Crop management practices

Different crop management practices at appropriate stages of cultivation were carried out during the crop growing seasons and these are mentioned in the succeeding paragraphs with appropriate headings.

3.8.1. Land preparation

The land of the experimental field was prepared by removing the stubbles of the previous crop and was subsequently ploughed with tractor drawn mould board plough. Breaking the clods by means of a cultivator followed this operation. Seed beds were prepared with proper drainage and irrigation facilities. The interval between two consecutive sowing dates was two weeks. The layout of the experimental field (Fig. 3.3) was done and plots are allocated randomly to the four different cultivars of aromatic rice.

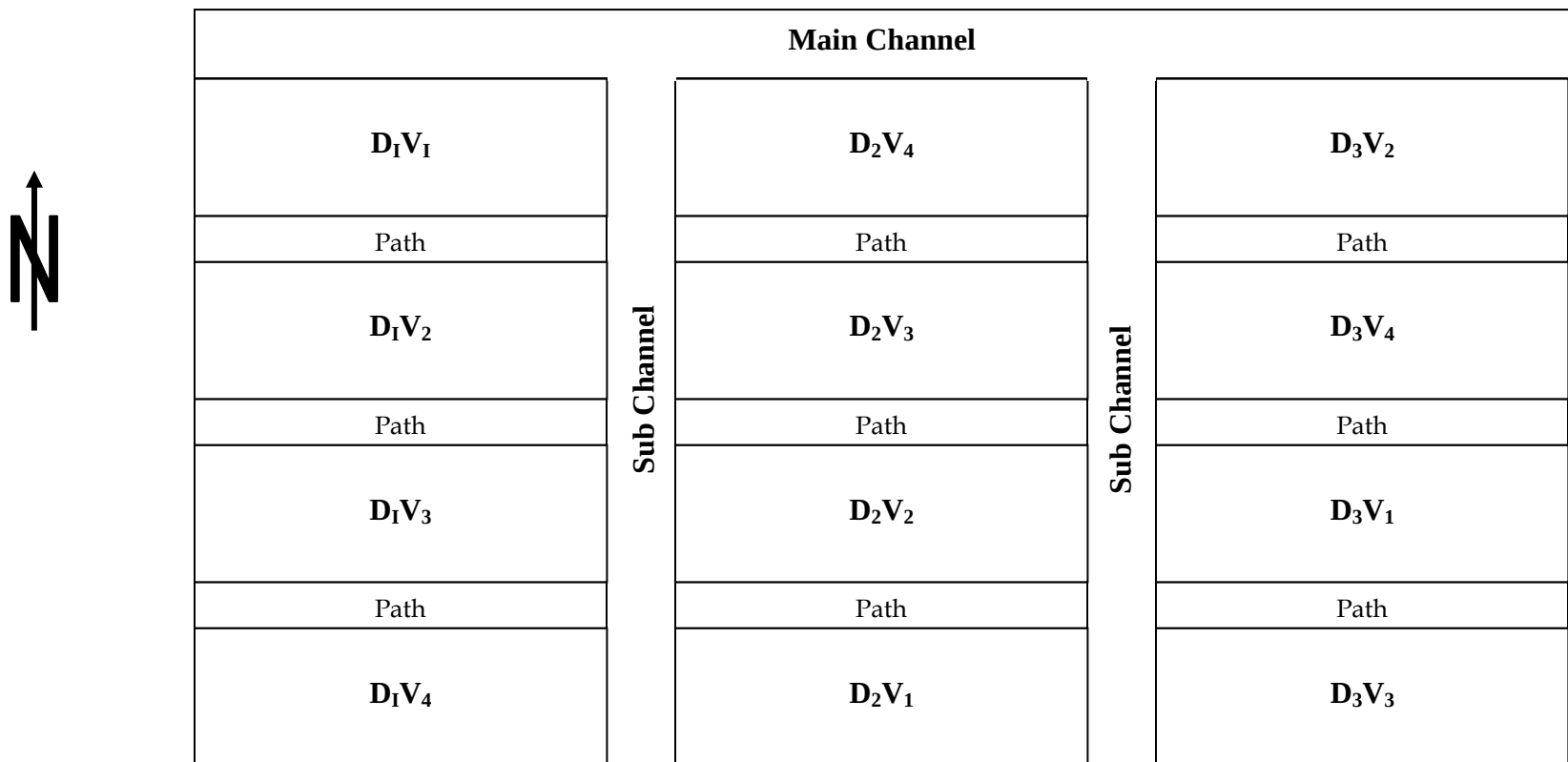


Fig 3.3: Experimental layout

3.8.2. Application of fertilizers

The fertilizer doses were same for all the varieties and dates of transplanting. Fertilizer doses used for seed bed and main field have been presented in the Table 3.4.

Table: 3.4: Fertilizer doses (kg ha⁻¹) for seed bed and main field

Fertilizer	Seed bed	Main field
N	50	60
P ₂ O ₅	25	30
K ₂ O	25	30

The sources of fertilizers used in the experiment were urea for N, single super phosphate for P₂O₅ and muriate of potash for K₂O.

3.8.2.1. For seed bed

Full dose of phosphate and potash and half of nitrogen were applied before final land preparation. Remaining half of nitrogen was applied 10 days before transplanting.

3.8.2.2. For main field

Full dose of phosphate and potash and 25% of total nitrogen were applied as basal before final land preparation (puddling), 50% of total nitrogen was applied 21 days after transplanting, i.e. at maximum tillering stage and rest 25% of total nitrogen was applied at panicle initiation stage.

3.8.3. Seed bed preparation and sowing of seeds

Seed beds were prepared with proper drainage and irrigation facilities. The interval between two consecutive sowing dates for both crop seasons were two weeks. The dates of sowing were June 12th, June 27th and July 12th of 2007 and 2008.

3.8.4. Transplanting and spacing

Transplanting was done with 25 days old seedlings for all the dates of sowing in both the crop years. The crop was transplanted with 3 seedlings /hill in 20 cm apart rows where hills were spaced at 10 cm apart in both the years. The row direction was East-west for all the treatments.

3.8.5. Cultural operations

3.8.5.1. Irrigation

The crops received 1046.1, 964.1 and 609.4 mm rainfall in D₁, D₂ and D₃ transplanting respectively during the crop season of 2007, where as corresponding values were lower i.e., 600.4, 582.4 and 543.0 mm in D₁, D₂ and D₃ transplanting respectively during the crop season of 2008. However, irrigation were given, whenever necessary, to maintain a water depth of 0-5 cm.

3.8.5.2. Weeding and hoeing

Hand weeding was done to remove all weeds. No herbicide was applied to control weeds. Hand weeding was done at 20 days after transplanting, i.e., just before the day of first topdressing.

3.8.5.3. Control of pest and diseases

Table 3.5: Control measure of pest and diseases

Name of pests and diseases	Chemicals used	Rate of application	Applied at
1. Stem borer	Monocrotophos 40 EC	@ 1.5 ml/lit	Nursery phase
2. Rice hispa	Endosulfan 35 EC	@ 2.0 ml/lit	10 days after transplanting
3. Brown plant hopper	Dichlorvos 76EC	@ 0.75 ml/lit	Beginning of tillering
4. Green plant hopper	Chloropyriphos 1.5 % P	@ 14.0 kg/ha in water solution	Maximum tillering
5. Blast	Edifenphos 50 EC	@ 1.0 ml/lit	Anthesis

Rice crop was affected by several pests and diseases. The details of the pests and diseases observed during the entire period of experimentation and their control measures have been summarized in Table 3.5.

3.8.6. Harvesting and threshing

The crop was harvested when more than 80% grains of panicles were fully matured and moisture content of the grain was about 20-25 per cent. The crop was harvested by leaving one border rows from two sides and four border hills from another two sides from each plot. After threshing, the grains were dried in the sun for several days and paddy (rough rice) yields have been expressed at 14% moisture (Anon., 2006a) level.

3.9. Crop assessment studies

It is the study of timing of recurring natural phenomena such as flowering or senescence of a crop (Munn, 1970). Information of crop phenology is essential for evaluating crop productivity and crop management.

3.9.1. Phenological observations

The phenological phases (or stages) of plant development and the observations thereof were recorded by visiting the field frequently from sowing to harvesting. Different phenophases like seed germination, emergence of seedlings, emergence and number of leaves, panicle initiation, flag leaf emergence, booting, heading, anthesis, milking, and dough stages, seed coat hardening and physiological maturity were recorded. In the seed bed, germination, seedling emergence and emergence of leaf in the main stem were also recorded. After transplanting, 20 hills were tagged with aluminium sheet in each plot to record the dates of appearance of various phenophases.

The whole life cycle of the rice crop from sowing to maturity was divided into six distinct phenophases are as follows:

EM = Emergence

EJ = End of juvenile phase

PI = Panicle initiation

AN = Anthesis

BGF = Beginning of grain filling and

PM = Physiological maturity

3.9.2. Crop growth observations

Crop growth may be defined as the irreversible increase in dry weight with time. Growth analysis is a technique for quantifying components of plant growth from a series of mathematical equations. The equations used for growth study have been described below. The crop growth observations recorded in this investigation were leaf area index (LAI) and above ground dry matter production at above phenophases.

3.9.2.1. Leaf area index (LAI)

LAI is the ratio between the area of the surface of green leaves and ground area covered. The following equation was used for calculation of leaf area index (LAI):

$$\text{LAI} = \frac{\text{Total green leaf area of the plants (cm}^2\text{)}}{\text{Total ground area (cm}^2\text{)}}$$

LAI is a pure number and has no unit. This equation was developed by Radford (1967) and it provided meaningful way of analyzing growth in crops. To study the leaf area indices for different dates of transplanting as well as for different varieties in both crop season, The green plants (three hills) were uprooted and green leaves were separated and their area was measured with leaf area meter (LI-COR 3100). While taking the samples care was taken to leave border rows

and border hills to avoid border effects. The sampling was done at various phenophases described above starting from emergence up to harvesting from each plot grown.

3.9.2.2. Above ground biomass

To assess the above ground biomass production the same plants uprooted for LAI measurement were used to record above ground biomass. The plants were washed and then roots were separated from the culms at the collar region. The leaves, stem, and panicles were separated and initially shade dried. They were then dried in oven at 65°C for 72 hours till a constant weight was obtained and expressed in g plant⁻¹. Number of leaves was also recorded.

3.10. Growth, yield and yield components

Growth in plants has various phases which start with activation of the embryo and ends with maturation of the seed. The processes involved in growth are very complex and are influenced by environmental factors. So the growth of plants directly and/or indirectly influenced yield components which ultimately determines final yield of the crop.

3.10.1. Number of panicles

The number of panicles/m² was counted just before harvest. The panicles were counted from four spots each of one m² area in each plot with the help of a one square meter quadrat. From these values the average number of panicles per plot was determined.

3.10.2. Number of grains/panicle

For determining the numbers of grains per panicle 20 panicles were sampled randomly from each plot separately. Both filled spikelets (grains) and unfilled spikelets (chaffs) were separated out and counted.

3.10.3. Test weight

To determine the test weight of grains, 1000 seeds from each plot

was counted and dried until constant weight was obtained. The weight of 1000 grains was recorded at 14% moisture level.

3.10.4. Grain yield

After threshing, grains were dried in the sun until the constant weight was obtained and then grains were weighed and converted into kilogram per hectare after adding the grain yield which could be contributed by the plants uprooted for sampling purpose.

3.10.5. Straw yield

After threshing, the straw of each net plot was dried in the sun till the constant weight was obtained. The straw from each plot was weighed separately and converted into kilogram per hectare after adding the straw yield which could be contributed by the plants uprooted for sampling purpose.

3.10.6. Harvest index (HI)

The total dry matter produced by a crop is known as biological yield and a fraction of the biological yield which is useful for human beings is known as economic yield. Harvest index may be defined as the ratio between economic yield and the biological yield. It is generally expressed as fraction and sometimes as percentage.

$$HI = \frac{\text{Economic yield (grain yield)}}{\text{Biological (grain + straw) yield}}$$

3.11. Statistical analysis

The data generated through the field experiment for two seasons were processed and analysed individually as well as for pooled basis to ascertain the high yielding cultivar and the optimum date of transplanting with respect to grain, straw and above ground biomass

yield. Comparisons were made between simulated data of various parameters viz., yield, periodic dry matter, above ground biomass production, periodical and maximum LAI, test weight, harvest index, grains per panicle, grain weight and number per sq. meter and their corresponding observed data through regression analysis. Measures of accuracy were worked out with correlation coefficient (r) and index of agreement (D) (Willmott, 1982).

3.12. CERES- Rice model

A computer based crop model CERES (Crop Environment Resource Synthesis) rice (IBSNAT and DSSAT) was used to simulate the growth, development and yield of four different cultivars of aromatic rice under middle Gujarat agroclimatic region by taking into account the effects of weather, management and genetics. Since the focus of this research is on performance of selected cultivars and applications of this model under middle Gujarat agroclimatic region, therefore soil water, carbon and nitrogen routine was switched off during simulation. Since the initial configuration of the model was suited to simulate the performance of longer duration cultivars of rice, it couldn't be fitted for above selected cultivars under this agroclimatic region as such. Thus for making the model suited to these varieties of aromatic rice being grown under the agroclimatic conditions of this region, lot of efforts were made to create the required input files and to modify several initial values pertaining to the weather, soil, genotypes and management practices. Minimum crop performance data set are required for determining the values of the phenology coefficients initially and then the values of the coefficients describing growth and grain development include dates of emergence, anthesis, beginning of grain filling, maturity duration, grain yield, above ground biomass, grain density and weight. The procedure for determining genetic coefficients involved in running the model using

a range of values of each coefficient, in the order indicated above, until the desired level of agreement between simulated and observed values was reached. Iterations for the coefficients were stopped when the agreement reached $\pm 10\%$. For the present study the cultivar genetic coefficients based on field experimental data of first crop season (*Kharif*, 2007) for four different cultivars of aromatic rice (described in experimental details above) had been carried out by trial and error as per Hunt's (Hunt *et al.*, 1993) method.

DSSAT v.3.5 consists of many different applications, including data programs, various crop simulation models and analysis programs for Agrotechnology transfer. The following is a very brief description of DSSAT v.3.5 CERES-Rice models.

3.12.1. Brief description of CERES- Rice model

The CERES-Rice model (Ritchie and Otter, 1985; Ritchie, 1986 and Godwin *et al.*, 1990) was adopted as the basis to simulate the effects of cultivar, planting density, weather, soil water and nitrogen on crop growth, development and yield. CERES- Rice model shared a common input and output data format, which had been developed and embodied in a software package called Decision Support System for Agro-technology Transfer (DSSAT). The DSSAT (IBSNAT, 1989; Jones, 1993 and Tsuji *et al.*, 1994) is a shell that allows the user to organize and manipulate crop, soil and weather data and run the crop models in various ways to give their outputs. It was developed for yield prediction and control at the farm and regional level. The primary purpose of the model is to predict potential alternative management strategies and tactics that affect yield and also the intermediate steps in the yield formation process. It is also intended to be useful at the farm level for crop decision-making and multiyear analysis for risk assessment. On a regional basis it is intended to be useful for yield forecasting and for the analysis of various policy

questions related to crop production and resource conservation. With declining profitability of agricultural produce and with natural resources becoming scarce, farm managers and regional policy planners require new tools to assist them in decision making. Simulation models that can capture the major edaphic and genetic effects on crop growth as well as the nuances of weather offer good opportunities for assisting farm managers in several aspects of decision making.

3.12.2. Minimum data required for operation and evaluation of CERES-Rice model

The minimum data requirements for operation, calibration and validation of the CERES Rice-models are provided by Hunt and Boote (1994) described in Table 3.6.

Table: 3.6: List of input required by CERES-Rice model

Input variables	Acronyn	Units
1. SITE DATA		
Latitude	LAT	Degree
Longitude	LONG	Degree
Elevation	ELEV	m
Average air temperature	TAV	°C
Height of temperature measurement	TMHT	m
Height of wind measurement	WMHT	m
CO ₂ concentration		ppm
2. DAILY WEATHER DATA		
Maximum temperature	TEMPMAX	°C
Minimum temperature	TEMPMIN	°C
Solar radiation	SOLARAD	MJ m ⁻² day ⁻¹
Rainfall	RAIN	mm
Wind speed	WRUN	Km h ⁻¹
Relative humidity (morning)		%
Relative humidity (afternoon)		%
Dew point temperature	TDEW	°C
Photosynthetic active radiation (PAR)	PAR	MJ m ⁻² day ⁻¹
3. SOIL CHARACTERISTICS		
Soil texture	SLTX	
Soil local classification	SLDESC	
Soil family SCS system	TACON	
Soil depth	SLDP	m

Colour, moist	SCOM	
Albedo (fraction)	SALB	
Evaporation limit	U	cm
Drainage rate (fraction day ⁻¹)	SWCON	
Runoff curve number	CN2	
Mineralization (0 to 1 scale)	SLNF	
Photosynthesis factor (0 to 1 scale)	SLPE	
pH in buffer determination method	SMPX	
Potassium determination method	SMKE	
Horizon-wise		
Lower limit drained	LL(L)	cm ³ /cm ³
Upper limit drained	DUL(L)	cm ³ /cm ³
Upper limit drained	SAT(L)	cm ³ /cm ³
Saturated hydraulic conductivity	SWCN(L)	cm hr ⁻¹
Bulk density moist	BD(L)	g cm ⁻³
Organic carbon	OC(L)	%
Clay (<0.002 mm)	CLAY(L)	%
Silt (0.05 to 0.002 mm)	SILT(L)	%
Coarse fraction (>2 mm)	STONES(L)	%
Total nitrogen	TOTN(L)	%
pH in buffer	PHKCL(L)	
Cation exchange capacity	CEC(L)	Cmol kg ⁻¹
Root growth factor 0 to 1	SHF(L)	
4. MANAGEMENT DATA		
Sowing date	YRPLT	
Emergence date	IEMERG	
Plant population at seedling	PLNATS	Plant m ⁻²
Planting method (TP/direct seeded)	PLME	
Planting distribution (row/broadcast/hill)	PLDS	
Row spacing	ROWSPS	cm
Row direction (degree from north)	AZIR	
Plants per hill	PLPH	
Seed rate	SDWTRL	Kg ha ⁻¹
Sowing depth	SDEPTH	cm
Irrigation dates	IDLAPL	
Irrigation amount	AMT(J)	mm
Method of irrigation	IRRCOD	
Fertilizer application dates	FDAY(J)	
Fertilizer amount N	ANFER	Kg ha ⁻¹
Fertilizer type	IFTYPE	
Fertilizer application method	FERCOD	

Fertilizer incorporation depth	DFERT	cm
Tillage date	TDATE	
Tillage implement	TIMPL	
Tillage depth	TDEP	cm
Residue management	LNRES	
Chemical applications	LNCHE	
Environment modification	LNENV	
5. HARVEST DETAILS		
Harvest	HDATE	
Harvest stage	HSTG	
Harvest component	HCOM	
Harvest percentage	Kg ha ⁻¹	

3.12.3. Overview of CERES-Rice model operations

The model consists of a series of subroutines with separate subroutines for each major process. In addition to this, there are subroutines associated with input and output and have user-friendly interface. The names and functions of each of these subroutines and the interlinkages among them are indicated in the flowcharts shown in Fig. 3.4 to 3.8 (<http://nowlin.csu.msu.edu>, 2004).

The input system enables the user to interactively select crop genotypic, weather, soil and management data appropriate to the experiment being studied (Fig. 3.4). After selection of the appropriate inputs, the model initializes the necessary variables for growth, water balance, and soil nitrogen dynamics simulation and displays these parameters for checking before commencing simulation (Fig. 3.5). Following initializations, a daily simulation loop is entered in which one-day's weather data are read and then all calculations on water and N balance, crop growth and development are performed (Fig. 3.6.A and 3.6.B). A series of switches is used to route execution to different subroutines depending upon the stage of development of the crop and upon whether the soil profile is draining. After these calculations are completed, output may be written to the output files (Fig. 3.7).

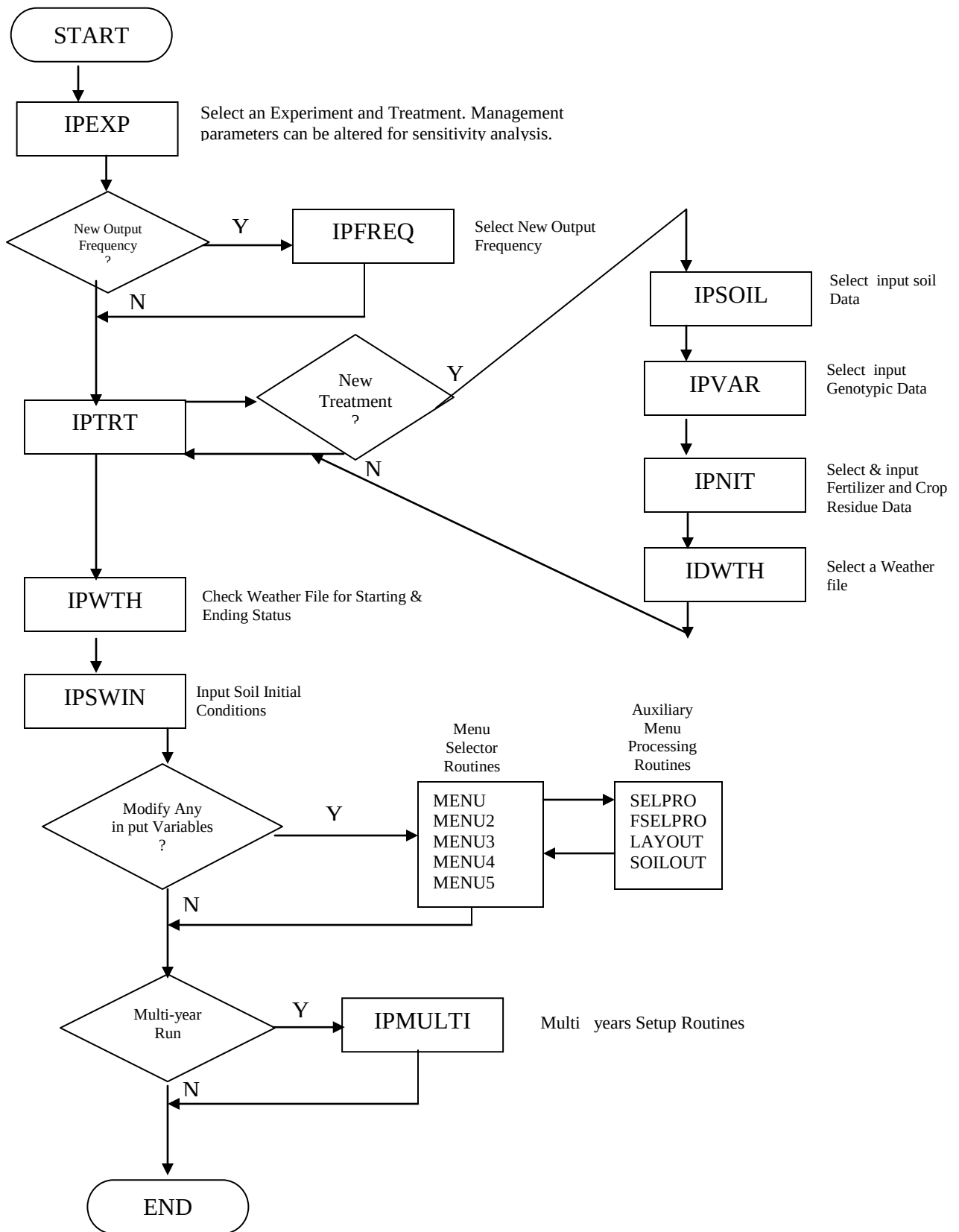


Fig 3.4: Flow chart of experiment and treatment selection

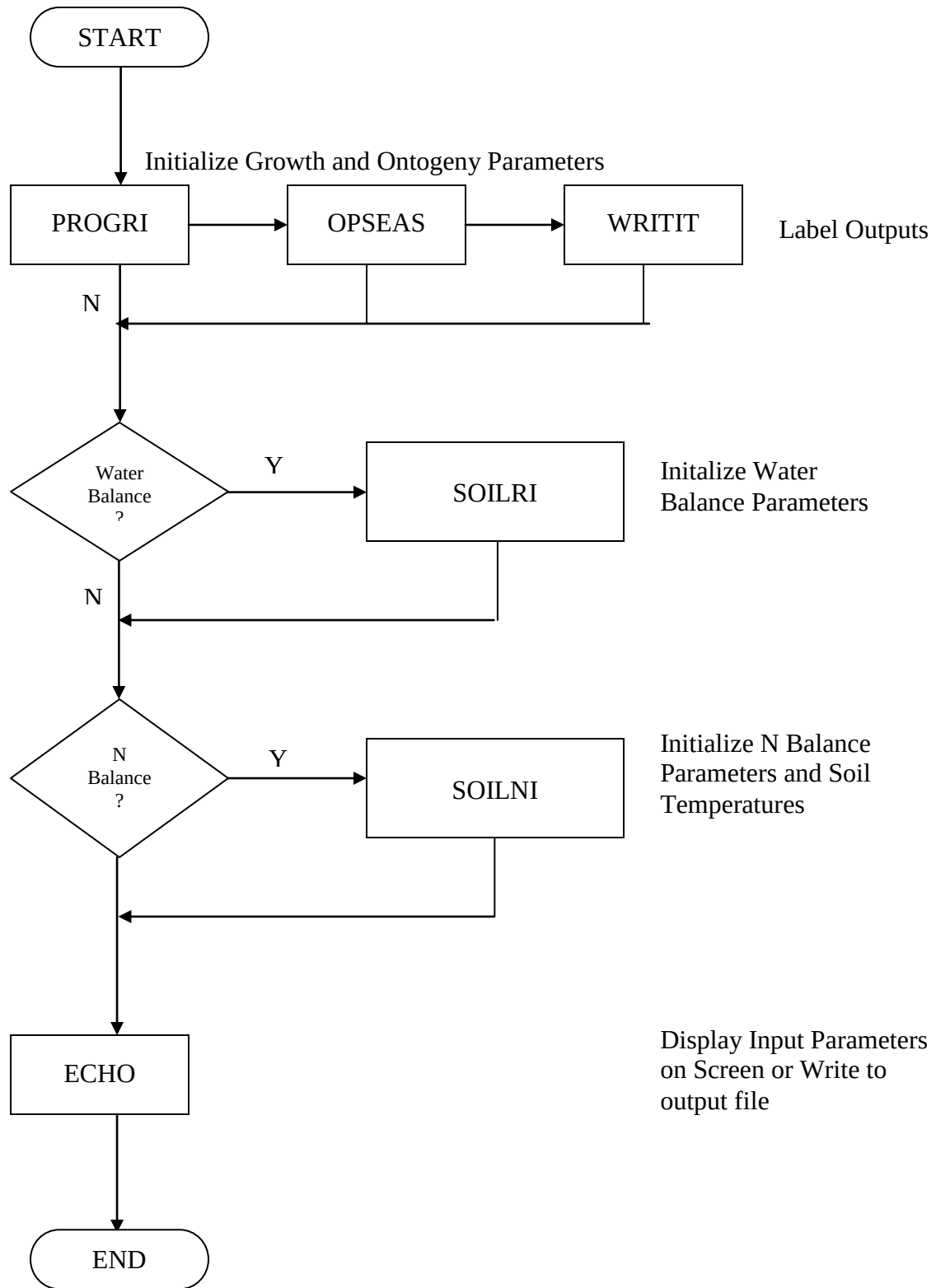


Fig 3.5: Flow chart

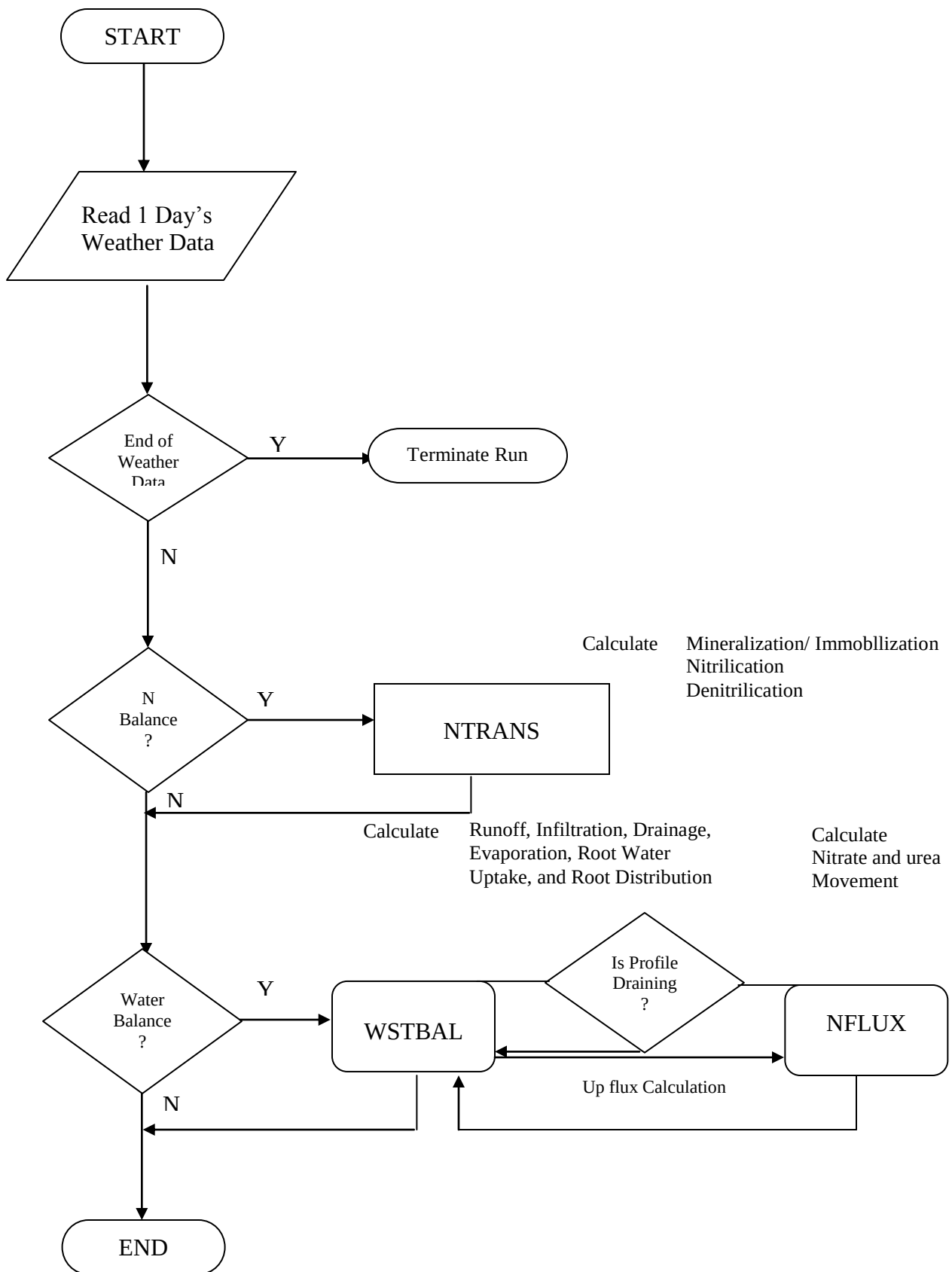


Fig 3.6 A: Flow chart showing daily simulation of various parameters based on weather data

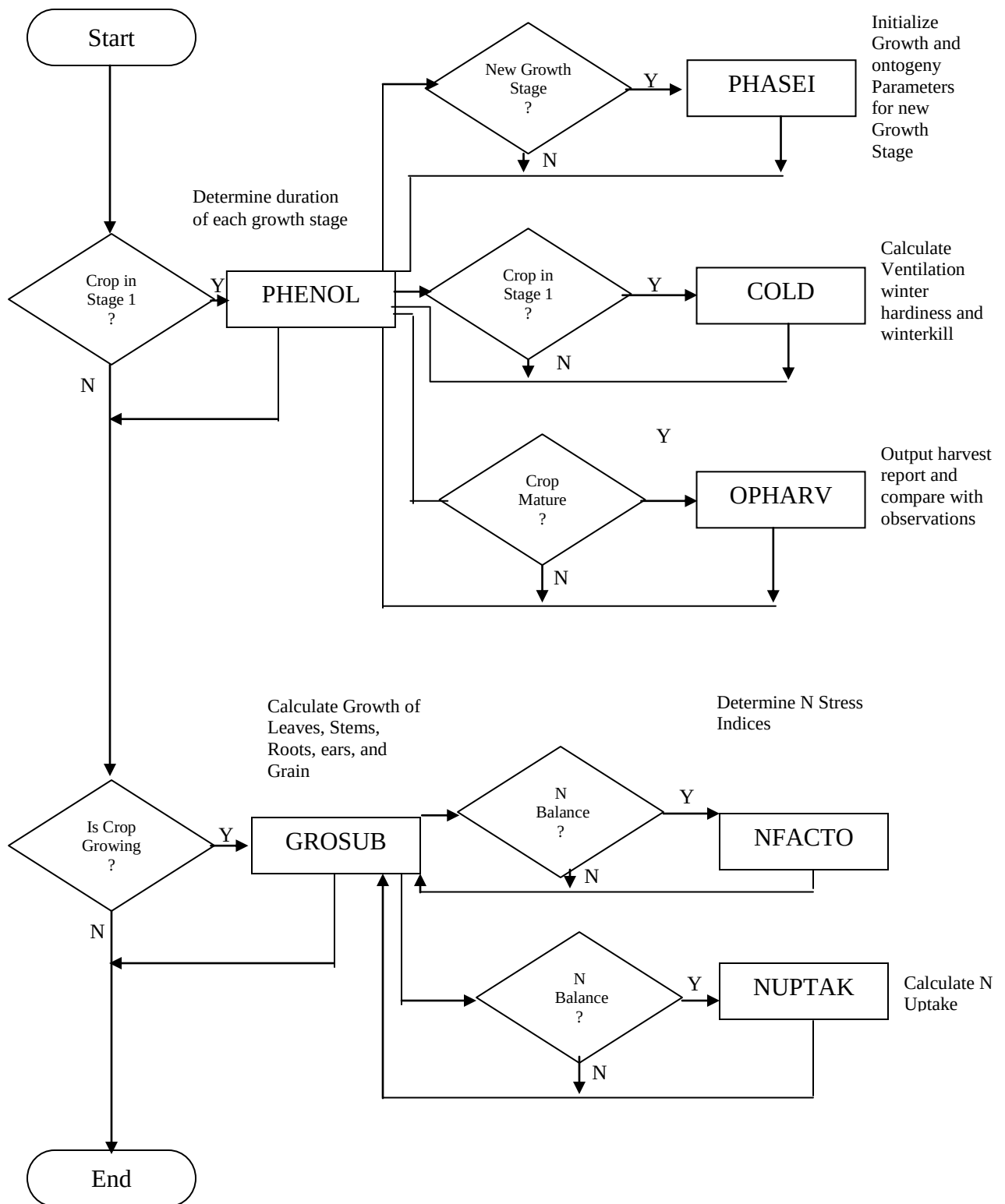


Fig 3.6 B: Flow chart showing daily simulation of various parameters based on weather data.

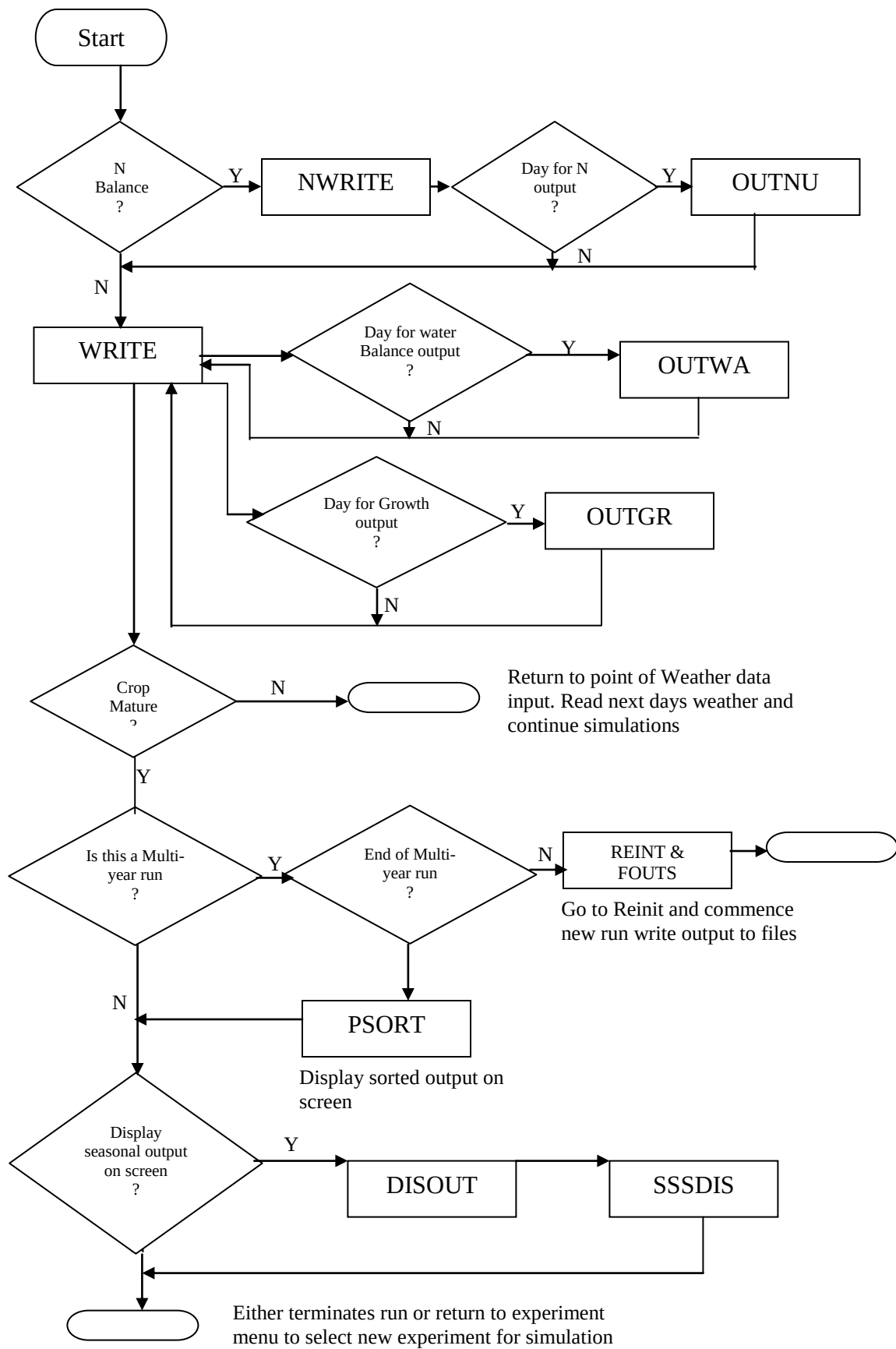


Fig 3.7: Flow chart of various output files

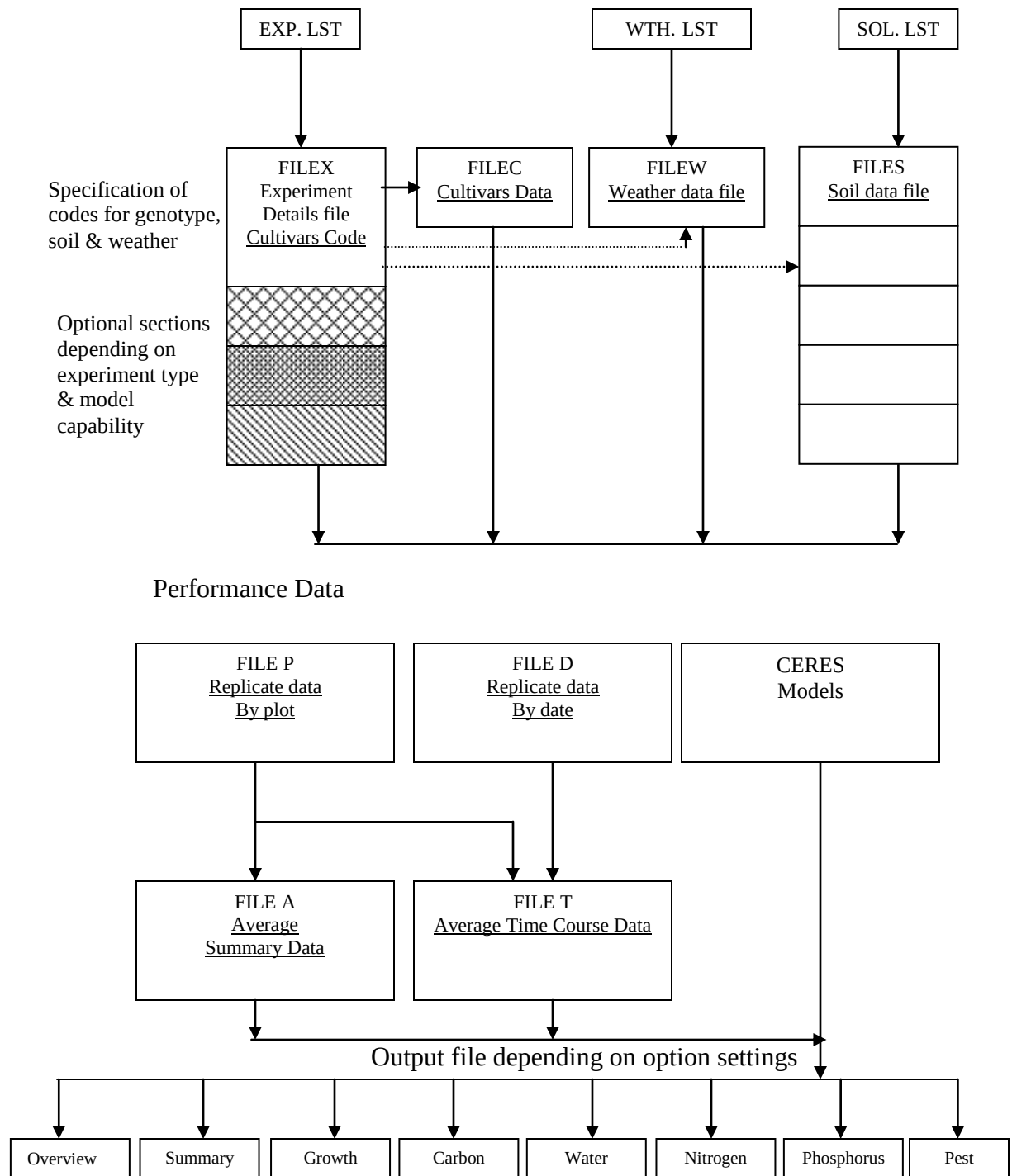


Fig 3.8: Overview of input and output files used by CERES-Rice model

The model is run on IBM PC compatible computer under MS-DOS. The model can be run for single treatment, multiple treatments and multiple years run simulation. Through the model, various crop processes are simulated based on many mathematical and logical equations relating the different equations by a stress scaling factor 0-1.

3.12.4. CERES-Rice input and output files

The files are organized into input, output and experiment performance data file. A typical organization of these is depicted in Fig. 3.6. The experiment performance files are needed only when simulated results are to be compared with data recorded in a particular experiment. In some cases, they could be used as input files to reset some variable during the course of a simulation run. Model input files are organized to allow some flexibility in their use with specific models. For example, there is a soil nutrient management section that users could eliminate when their crop model does not include a soil fertility component.

The input files are further divided into those dealing with the experiment, weather and soil and the characteristics of different genotypes (Table 3.7). Similarly output files are also further divided into those dealing with the overview, summary, growth, water, carbon and nitrogen balance (Table 3.8).

Table: 3.7: CERES-Rice model input files

Sr. No.	Input	File name	Description
1	Experiment	FILEL	Listing of all available experiment details files e.g. EXP.LST
		FILEX	Experiment detail file for a experiment, treatments, field conditions, crop management and simulation control e.g., AAUN2007.RI & AAU2008.RI
2	Weather and soil	FILEW	Weather data daily for a specific station and time period e.g., AAUN2007.WTH & AAUN2008.WTH

		FILES	Soil profile data for a group of experimental sites or for a specific Institute e.g., SOIL.AAU
3	Crop and cultivar	FILEC	Cultivar coefficients for a particular crop species and model e.g. RICER980.CUL Rice for CERES model, version 980
		FILEE	Ecotype specific coefficients for a particular crop species and model e.g. RICER980.ECO. Rice for CERES model, version 980
		FIELG	Crop (species) specific coefficients for a particular model. e.g., RICER980. SPE. Rice for CERES model, version 980

Table: 3. 8: CERES-Rice model output files

Sr. No.	Output	File name	Description
1	Overview	OUTO	Overview of inputs and major crop and soil variables e.g., OVERVIEW. OUT
2	Summary	OUTS	Summary information: Crop and soil input and output variables. e.g., SUMMARY.OUT
3	Growth	OUTG	Detailed time-sequence information on growth e.g., GROWTH.OUT
4	Water	OUTW	Detailed time-sequence information on water balance e.g., WATER.OUT
5	Carbon	OUTC	Detailed time-sequence information on carbon balance e.g., CARBON.OUT
6	Nitrogen	OUTN	Detailed time-sequence information on nitrogen balance e.g., NITROGEN.OUT

The detailed information on experiment performance files are given in the following Table 3.9.

Table: 3.9: CERES-Rice model experiment data files

Sr. No.	File name	Description
1	FILEP	Performance data (replicate values arranged by plots) e.g., UFGA8801. SBP
2	EILED	Performance data (replicate values arranged by date) e.g., UFGA8801.SBD

3	FILEA	Average values of performance e.g., UFGA8801.SBA
4	FILET	Time course data of experiment e.g., UFGA8801.SBT

3.12.5.1. Experiment directory file

The file EXP.DIR contained the description of the experiment and names of input and output files. All the entries were replaced with the new entries pertaining to the present situations.

3.12.5.2. Weather directory file

The file WTH.DIR contains a list of weather files of different locations for different years. Weather files created for the years 2007 and 2008 pertaining to the Nawagam situation were included in the list of weather file as follows.

Weather file consisted of the daily solar radiation, temperature (max. & min.) and rainfall. New weather files AAUN2007 and AAUN2008 were created for crop year 2007 and 2008 respectively. Daily weather parameters from January 1 to December 31 were entered in the file.

3.12.5.3. Soil properties directory file

The file SOIL.SOL contained the list of different soils with their physical and chemical properties .A new entry “Deep silty loam of Nawagam” was included as AAUN002007. Physical and physicochemical properties along with initial soil nitrate and ammonical nitrogen contents were entered for each layer of soil in the proper format.

3.12.5.4. Soil profile initial condition file

The soil profile initial condition file contained the initial values of soil water, soil reaction and soil nitrogen data pertaining to this situation was entered.

3.12.5.5. Irrigation management file

The Irrigation management file has the provision of date and amount per fixed irrigation (mm) applied depth (cm) of management. Irrigation data pertaining to this situation was entered.

3.12.5.6. Fertilizer management file

The fertilizer management file contained the date, form and amount of nitrogen application. Accordingly information on fertilizer application was entered in the file.

3.12.5.7. Treatment management file

The treatment management file contained the description of each treatment under separate title and serial numbers. The file also contained dates of planting and emergence, plant population at seeding and at emergence, planting method, planting distribution, row spacing, row direction, planting depth, planting material, transplant age, plants per hill, dates of simulation beginning etc. All needed information was entered for all the treatments.

3.12.5.8. Crop cultivars directory file

The file RICER980-CUL contained the list of different rice cultivars with their genetic coefficients. Four separate entries AAUN01, AAUN02, AAUN03 and AAUN04 were incorporated in this file under serial number 38, 39, 40 and 41 for Pankhali, Narmada, GR-104 and Pusa Basmati-1 respectively. The modified genetic coefficients viz., P1, P2R, P2O, P5, G1, G2, G3 and G4 (described in calibration part of this chapter) were entered against the new entry. The genetic coefficients are the most important parameters which represents the genetic characteristics of the particular cultivar and on which the crop phenology, biomass production partitioning and yield potential of the crop depends (Edmeades and Dayanand, 1979; Rosenthal *et al.* 1989). However, the actual performance is controlled by the external factors also. Since determination of these

genetic characteristics requires intensive experiment under controlled conditions, it was not determined for the aromatic cultivars of paddy.

The values of this coefficients pertaining to a particular paddy cultivars are expected to vary within this range which could be found out by trail and error methods (Jones and Kinery, 1986). Accordingly number of permutations and combinations were tried. For each trial the output values of the model particularly the crop duration and biomass production, were compared with observed values of respective cultivars. It was experienced that slight change in the values of a coefficient resulted into large variation in the output summary. Out of hundreds of such trial the most suitable combination of these coefficients were selected to run the model for both crop years which have been presented in Table 3.11. Adoption of these coefficients represented almost truly the Pankhali, Narmada, GR-104 and Pusa Basmati-1 cultivars of aromatic rice as it produced matching crop summary with the observed data, when the model was run for several crop years.

3.12.5.9. Field observed data file

The field observed data file is meant for entry of observed data on crop performance and nitrogen uptake. If these data are entered the model output gives a comparative table through which simulated and observed values can be compared. Under the present investigation observed data on crop performance for all the treatments were entered.

3.12.6. Running the crop model

Once, all the desired files were created carefully the model was run for all the treatments. For this, the command AAUN2007.RI & AAU2008.RI for the crop year 2007 and 2008 respectively was given and the model was executed and a menu appeared on the screen which contained serial number and titles of the experiment with their treatments details. Selecting the serial number, all the treatments were run one after

another. Each run of model created four output files containing the different aspects of crop simulation such as; biomass production and its partitioning, weather parameters with soil water balance and nitrogen balance. The details of output files are as follows.

3.12.6.1. Output file-1

The output file OUT1.RI contained the experimental and treatments details, crop summary, simulated crop phenology, crop performance and comparison between observed and predicted values.

3.12.6.2. Output file-2

The output file OUT2.RI contained the detailed crop performance summary with respect to biomass production, its portioning and leaf area indices at a given frequency.

3.12.6.3. Output file-3

The output file OUT3.RI contained the simulated information on soil water balance along with actual values of solar radiation, temperature and precipitations.

3.12.6.4. Output file-4

The output file OUT4.RI contained the simulated nitrogen balance with respect to vegetative N-uptake, grain N-uptake and layer wise soil nitrogen contents at a given frequency from sowing to harvesting. However, Nitrogen subroutine was remained switched off in this present study.

3.12.7. Calibration of the CERES Rice model

Model calibration or parameterization is the adjustment of parameters so that simulated values compare well with observed values. The genetic coefficients that influence the occurrence of developmental stages in the CERES models were derived iteratively, by manipulating the relevant coefficients to achieve the best possible match between the simulated and observed number of days to the phenological events. Other coefficients were derived from determinations of non-limited grain

Table: 3.10: Genetic Coefficients for the CERES Rice model

P1	Time period (expressed as growing degree days [GDD] in °C above a base temperature of 9°C) from seedling emergence to end of juvenile phase during which the rice plant is not responsive to changes in photoperiod. This period is also referred to as the basic vegetative phase of the plant.
P2R	Extent to which phasic development leading to panicle initiation is delayed (expressed as GDD in °C) for each hour increase in photoperiod above P2O.
P2O	Critical photoperiod or longest day length (in hours) at which the development occurs at maximum rate. At values higher than P2O the development rate is slowed (depending on P2R), there is delay due to longer day length.
P5	Time period in GDD in °C from beginning of grain-filling (3-4 days after flowering) to physiological maturity with base temperature of 9°C
G1	Potential spikelet number coefficient as estimated from number of spikelets per g of main culm dry weight (less lead blades and sheaths plus spikes at anthesis. A typical value is 55.
G2	Single dry grain weight (g) under ideal growing conditions. i.e., non limiting light, water, nutrients, and absence of pests and diseases.
G3	Tillering coefficient (scalar value) relative to IR64 cultivars under ideal conditions. A higher tillering cultivar would have coefficient greater than 1.
G4	Temperature tolerance coefficient. Usually 1.0 for cultivars grown in normal environment. G4 for japonica type rice grown in warmer environments would be ≥ 1.0 . Tropical rice grown in cooler environments or season will have $G4 < 1.0$

weight and number of grains per panicle (rice). Alternatively, genetic coefficients can be determined using the GENCALC software that uses the observations of phenological events from one or several experiments from a range of environments (Hunt and Pararajasingham, 1994). The DSSAT shell includes default genetic coefficients for a range of species and cultivars, and the model user can also develop estimated coefficients for local conditions from the default coefficients. Many commonly grown cultivars are not included in the DSSAT shell, many of the cultivars that are included are not commonly grown, and the source of the genetic coefficient is not provided. The DSSAT shell contains genetic coefficients for very few varieties of rice and wheat grown in rice-wheat areas of Asia and Australia (Timsima and Humphreys, 2003). The details of genetic coefficients of CERES Rice model are presented in the above Table 3.10.

Table: 3.11. Genetic coefficients for four different cultivars of aromatic rice at Nawagam (middle Gujarat agroclimatic) condition

Cultivars	Parameters							
	P1	P2R	P2O	P5	G1	G2	G3	G4
Pankhali (P 203)	750.0	60.0	350.0	11.7	27.0	0.0165	1.00	1.00
Narmada (Ambica)	630.0	90.0	340.0	11.8	32.0	0.0196	1.00	1.00
GR- 104	740.0	75.0	370.0	11.9	41.0	0.0226	1.00	1.00
Pusa Basmati-1	620.0	65.0	352.0	11.6	31.0	0.0230	1.00	1.00

Before models can be applied with confidence, they need to be calibrated and validated for the varieties and environments of interest. To calibrate genetic coefficients as mentioned in the present model for four cultivars of aromatic rice viz, Pankhali (P 203), Narmada (Ambica), GR 104 and Pusa Basmati-1 (described in experimental details above) had been carried out by trail and error method. The calibrated genetic coefficients based on field experimental data of 2007 crop year at Main

Rice Research Station, Nawagam condition are presented in the above Table 3.11.

3.12.8. Validation of the model

Validation is the comparison of the results of model simulations with observations from crops that were not used for the calibration. A model should be rigorously validated under widely differing environmental conditions to evaluate the performance of major processes in addition to its ability to predict yield (Timsima and Humphreys, 2003). Before any model can be used with confidence, adequate validation or assessment of the magnitude of the errors that may result from its use should be performed. Model validation, in its simplest form is a comparison between simulated and observed values.

Beyond comparisons, there are several statistical measures available to evaluate the association between predicted and observed values. Among them correlation coefficient (r) and its square, the coefficient of determination (R^2) are widely used parameters. Willmott (1982) has pointed out that the main problem with this analysis is that the magnitudes of r and r^2 are not consistently related to the accuracy of prediction where accuracy is defined as the degree to which model predictions approach the magnitudes of their observed counterparts.

Test criteria have been separated into two groups, called summary measures and difference measures. Summary measures include the mean of observed values ($\bar{O}$) and predicted values ($\bar{P}$), the standard deviation of observations (S_o) and the predictions (S_p), the slope (b) and intercept (a) of the least square regression ($P_i = a + b + O_i$).

Willmott (1982) calculated an index of agreement (D) as follows.

$$D = 1 - \left[\frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (IP_i' I + IO_i' I)^2} \right]$$

$$0 \leq (D) \leq 1$$

where,

$$P'_i = P_i - P \text{ and } O'_i = O_i - O.$$

The summary measures describe the quality of simulation while the difference measures try to locate and quantify errors. The latter include the mean absolute error (MAE), the mean bias error (MBE) and the root mean square error (RMSE). They were calculated according to Willmott (1982) as follows and were based on the terms $(P_i - O_i)$;

$$MAE = \sum_{i=1}^n [1P_i - O_i] / n$$

$$MBE = \sum_{i=1}^n [P_i - O_i] / n$$

$$RMSE = \left[\sum_{i=1}^n (P_i - O_i)^2 / n \right]^{1/2}$$

MAE and RMSE indicate the magnitude of the average error, but provide no information on the relative size of the average difference between (P) and (O) . The statistic MBE describes the direction of the error bias. The value of MBE is related to the magnitude of the values under investigation. A negative MBE indicates that the predictions are smaller in values than those of the corresponding observations. Varshneya (1999), who gave a simple indication of error in prediction, defined the percent Error (PE). PE is defined as ratio of RMSE to mean observed value expressed as percentage.

$$PE = \frac{RMSE}{\bar{O}} \times 100$$

The entire procedure as described above was carried out for the purpose of fulfilling the objectives of this investigation and pertinent results are described in the next chapter.

IV. RESULTS AND DISCUSSION

The present investigation was carried out during the *kharif* seasons of the years 2007 and 2008 with the prime objective of simulating the growth parameters and grain yields of four different cultivars of rice using the CERES-Rice model after calibrating genetic coefficients of rice cultivars using field experiment data carried out at Nawagam (Middle Gujarat Agro-climatic region) conditions. The results of grain yields and various yield attributing characters in terms of their respective actual values were compared with respectively those simulated by the model. The results are presented and discussed under titled paragraphs in pursuance of the objectives set forth for the study.

4.1. Weather conditions during crop seasons *kharif* 2007 and 2008

The daily weather data of both the crop growth seasons were collected from the Agrometeorological Observatory, Main Rice Research Station, Nawagam. The average of ten days was worked out for temperatures, sunshine hours, wind speed, mean vapour pressure and ten days total rainfall for graphical presentation. The daily values of weather parameters for both the years are presented in Appendix- I.

4.1.1. Air temperature

The range of daily mean temperature as obtained from the maximum and minimum temperatures of the pertinent day ranged from 24.6 to 34.4°C during the *kharif* season of 2007, while the corresponding range in the year 2008 was 25.4 to 31.7°C. The crop experienced higher

average maximum temperature of 35.0°C (ranging between 30.2 to 40.4°C) during the nursery phase in D₁ transplanting of the year 2007 (Fig. 4.1a), while this was 35.2°C (ranging between 31.6 to 37.5°C) in the same period of the crop growing season of the year 2008 (Fig. 4.3a). However, germination was not affected in any of the two crop seasons on account of continuous wet condition of nursery after sowing. Similarly under both the crop growing seasons, D₁ transplanting experienced the highest average maximum temperature of 32.9°C (ranging between 31.0 to 38.6°C) and 32.8°C (ranging between 30.4 to 35.8°C) for years 2007 and 2008, respectively. However, prevalence of high maximum temperature was more pronounced during nursery period as well as during physiological maturity phase (130 DAS) of the crop in both the crop growing seasons. The daily mean temperature was not decreased gradually from the date of sowing to physiological maturity among all the dates of transplanting, but considerably lower mean temperatures prevailed during the flowering and milking stage in D₂ transplanting (Fig. 4.1c and 4.3c). This showed that, more so in the second date of transplanting, and its beneficial effect was indirectly reflected in grain yield.

Lowest average minimum temperatures recorded were 17.3, 17.5 and 16.2°C in D₁, D₂ and D₃ during 140, 120 and 130 DAS, respectively in the year 2007, while these were 11.8, 16.4 and 15.6 °C in D₁, D₂ and D₃ transplanting at 140, 130 and 130 DAS in the second year experiment, respectively (Fig. 4.1b and 4.3b). A downward trend of the mean temperature was noticed from 130 DAS, 100 DAS and 100 DAS till the end of maturity in D₁, D₂ and D₃, respectively under both the years of study. The average maximum temperatures observed during the crop period 2007 under different dates of transplanting were 32.9, 32.5 and 32.8°C, respectively in the first, second and third dates of transplanting. The corresponding values during 2008 were 32.8, 32.9 and 32.6°C, respectively (Table 4.1). An overall behaviour of the maximum temperature during both the years revealed that in D₁ and D₃ transplanting slightly higher maximum temperature was recorded in 2007 while D₂ recorded slightly lower temperature when compared with that corresponding to the season of 2008.

The average values of minimum temperature that prevailed during the year 2007 *khariif* season under different dates of transplanting were 24.5, 23.8 and 23.2°C, respectively in the first, second and third date of transplanting. The corresponding values during 2008 *khariif* season were 24.4, 22.7 and 22.8°C, respectively (Table 4.1). The average minimum temperatures decreased from 10 DAS till harvest in the first date of transplanting where as downward trend were recorded from 20 DAS to 120 DAS and 20 DAS to 110 DAS in D₂ and D₃ respectively and it was later resumed an upward trend during 2007. The downward trend of average minimum temperature was recorded from 10 DAS to harvest among all the date of transplanting in 2008 crop season (Fig. 4.1b and 4.3b).

4.1.2. Sunshine hours

The values of the bright sunshine hours exhibited more fluctuations during the study period of 2008 as compared to those of the study period of 2007 (Fig. 4.2a and 4.4a). The average value of daily bright sunshine hours were 6.4 and 5.8 hours for 2007 and 2008 crop seasons respectively with very little variation from one date of transplanting to another (Table 4.1). Highest average values of sunshine hours (6.83 h) were recorded by D₃ transplanting during 2007, while D₁ had shown the lowest average values of sunshine hours (5.0 h) in the year 2008. The deviation of actual value from the mean was more pronounced in the beginning stages of crop growth during both the years. The average sunshine hours showed a difference ranging from 0.1 to 9.7, 1.7 to 9.7 and 1.8 to 9.7 (h) in D₁, D₂ and D₃ respectively during crop season 2007 whereas D₁, D₂ and D₃ recorded 1.0 to 9.3, 0.2 to 9.4 and 1.0 to 9.3 respectively from nursery till maturity during 2008 crop season (Fig. 4.2a and 4.4a).

Fluctuations in the values of sunshine hours from one date of transplanting to another date of transplanting remained very high up to

110 DAS during crop growing season of 2007, while in 2008 larger fluctuations were noticed up to 90 DAS and there after fluctuation among date of transplanting become more or less very marginal during both the crop season (Fig. 4.2a and 4.4a). The highest average bright sunshine hours were encountered by the crop in D₂ transplanting than that of D₁ and D₃ in crop season 2008 and D₁ in 2007 through out the crop season where as D₃ recorded highest corresponding value during crop season 2007.

4.1.3. Wind speed

The average wind speed during the crop-growing season varied considerably between the years and also among the different dates of transplanting of the same season. The average wind speed worked out for the crop-growing season as a whole, for each of the respective crop seasons showed decreasing trend from the first dates of transplanting to subsequent transplanting during both the crop season. It was 5.0, 4.3 and 3.8 kmph in the first, second and third dates of transplanting, respectively in crop season of 2007 (Table 4.1). The magnitude of fluctuations in wind speed was found high up to 70 DAS and thereafter it was found to be more or less low till harvest during both the crop growing seasons (Fig. 4.2b). Average wind speed of 5.6, 4.3 and 4.3 kmph was recorded in the first, second and third date of transplanting, respectively (Table 4.1). during the crop-growing season of 2008. Low wind speeds during the reproductive phase in D₂ transplanting resulted into higher grain yield of the crop during both the year.

4.1.4. Mean vapour pressure

The mean vapour pressure showed a fluctuating trend during both the years of the study. The average vapour pressure during all the dates of transplanting was higher during 2007 as compared to that of 2008 (Table 4.1). The highest values of average of mean vapour pressure as

recorded were 25.5, 25.8 and 25.5 mm of Hg in D₁, D₂ and D₃ at 90, 40 and 60 DAS, respectively in the crop-growing season of 2007 (Fig. 4.2c). Similarly, these values were 24.6, 24.8 and 24.6 mm of Hg remain prevalent during early reproductive phase of crop in D₁, D₂ and D₃ respectively in 2008 (Table 4.1). The second date of transplanting also encountered more or less constant lower mean vapour pressure than the D₂ transplanting during reproductive phase in both the crop year, while D₃ encountered higher fluctuation in mean vapour pressure during reproductive stage of crop although the values were remain lower than that of other dates of transplanting.

The lowest values of the average of the mean vapour pressure as encountered by the crop were 14.2, 14.0 and 12.1 mm of Hg in D₁, D₂ and D₃ during maturity phase respectively in the crop season 2007 (Fig. 4.2c). Correspondingly similar values recorded were 14.5, 12.1 and 11.6 mm in D₁, D₂ and D₃ transplanting respectively during the maturity phase of the crop in the crop season of 2008 (Fig. 4.4c).

4.1.5. Rainfall

The total annual rainfall was 1065.5 mm and its distribution was also very good through out the crop season in all the dates of transplanting during 2007, where as 651.3 mm total annual rainfall was recorded by the year 2008 and distribution of rainfall was very erratic through out the crop season under all the dates of transplanting. The total amount of rainfall was 1046.1, 964.1 and 609.4 mm in D₁, D₂ and D₃ transplanting respectively during the crop season of 2007, where as corresponding values were lower i.e., 600.4, 582.4 and 543.0 mm in D₁, D₂ and D₃ transplanting, respectively during the crop season of 2008 (Table 4.1).

The ten days total rainfall showed a fluctuating trend among dates of transplanting during both the crop season (Fig. 4.5a and 4.5b). The first

Results and discussion

date of transplanting received higher amount (1046.1 mm) of rainfall (Table 4.1) with erratic distribution during the crop season 2007 than that of D₂ and D₃, but D₂ received all the rain up to 100 DAS and maturity phase remain free from any rainfall and cloud. In the case of D₃ transplanting, the total rainfall (609.4 mm) which was received during the crop season was almost half of the D₁ and D₂ transplanting in the same crop year. The distribution of the rainfall was also not good and crop has received total rain during vegetative phase i.e., up to 80 DAS (Fig. 4.5a).

The total amount of rainfall was quite low in all the dates of transplanting in the crop year 2008 than that of corresponding dates of transplanting in 2007 (Table 4.1). Although, the distribution of the rain was little bit smoother in the case of D₁ than that of D₂ and D₃ transplanting. But the differences in the total amount of rainfall were not remarkable among dates of transplanting. Crop received all the rain during the vegetative stage (80 DAS) in the case of D₂ and D₃ transplanting where as, D₁ received rain up to early reproductive phase i.e., 100 DAS (Fig. 4.5b).

Table 4.1: Average values of various weather elements (Max. Temp., Min. Temp., Mean Temp., BSSH and Mean V.P.) prevailed and total rainfall occurred during crop growing period under various dates of transplanting in *kharif* 2007 and 2008

Dates of Transplanting	Weather elements						
	Max. Temp (°C)	Min. Temp (°C)	Mean Temp (°C)	BSSH (Hrs)	Wind Speed (Kmph)	Mean V.P. (mm)	Total Rainfall (mm)
	Crop season 2007						
D1	32.9	24.5	28.7	6.1	5.0	23.4	1046.1
D2	32.5	23.9	28.2	6.2	4.3	22.7	964.1
D3	32.8	23.2	28.0	6.8	3.8	21.8	609.4
Crop season	32.7	23.9	28.3	6.4	4.4	22.7	1065.5
Dates of Transplanting	Crop season 2008						
	Max. Temp (°C)	Min. Temp (°C)	Mean Temp (°C)	BSSH (Hrs)	Wind Speed (Kmph)	Mean V.P. (mm)	Total Rainfall (mm)
D1	32.8	24.4	28.6	5.0	5.6	22.7	600.4

D2	32.9	22.7	27.8	6.2	4.3	20.9	582.4
D3	32.6	22.8	27.7	6.1	4.3	21.1	543.0
Crop season	32.8	23.3	28.0	5.8	4.7	21.6	651.3

4.2. Field experimental results

The field experiment, which formed the basis of this investigation, was carried out during the *kharif* seasons of 2007 and 2008 in order to determine various characters pertaining to growth, development and yield of four different aromatic cultivars of rice crop on three dates of transplanting keeping the interval of fortnight. The objectives of the field experiment were to simulate the various parameters of growth and grain yields of various cultivars of rice and to find out best cultivar and optimum date of transplanting that resulted into highest yield on the basis of validation of the model performance and also to calibrate the genetic coefficients of various cultivars of rice (cv. Pankhali, Narmada, GR-104 and Pusa Basmati-1) for CERES-Rice model and also to test other model parameters. The experimental results, which formed the basis of the comparison with corresponding results simulated by the model, are described below.

It would be appropriate at this stage to state that the basic objective of conducting the field experiment was not to study the agronomy of the influence of dates of transplanting on yield and yield attributing character of various cultivars of rice but to characterize the micro environment involving a combination of the date of transplanting and various cultivars of rice crop that could contribute to high yield which could or could not necessarily be the highest on the basis of various possible combinations of these two parameters indirectly representing the environment. Hence in the description and discussion of the results of the field experiment complete and comprehensive details as are necessary for

bringing out the agronomic implications of the experimental results have not been described and discussed although the processed agronomical data are presented. For the sack of brevity, therefore the results of the field experiment have been described and discussed with a specific focus on the best cultivars of rice and the date of transplanting congenial to contributing to high yield so that the performance of the CERES-Rice model could primarily be tested with respect to that combination of the treatments.

4.2.1. Effect on grain yield of rice crop

The experimental results of grain yield of various cultivars of rice as influenced by different dates of transplanting are presented in Table 4.2. The grain yields of cv. Pankhali in the first date of transplanting (D₁) were 3075 kg ha⁻¹, second date of transplanting (D₂) 3725 kg ha⁻¹ and under third date of transplanting (D₃) 3425 kg ha⁻¹ during the crop season 2007. The corresponding values of yields were 2662, 3120 and 2747 kg ha⁻¹, respectively in 2008. The corresponding pooled values over two years were 2869, 3423 and 3086 kg ha⁻¹, respectively. D₂ transplanting yielded the highest (3725 kg ha⁻¹ in 2007 and 3120 kg ha⁻¹ in 2008) as compared to D₁ and D₃ transplanting. The results of the pooled grain yield over two years were also to be highest (3423 kg ha⁻¹) in D₂ transplanting compared with that recorded by the rest of the transplanting.

Table 4.2: Effect of dates of transplanting on grain yields of various cultivars of rice

Treatments		Grain yield (kg ha ⁻¹)		
Cultivars	Dates of Transplanting	2007	2008	Pooled
Pankhali	D1-8 th July	3075	2662	2869
	D2-22 nd July	3725	3120	3423
	D3-8 th August	3425	2747	3086
Narmada	D1-8 th July	3395	2924	3160
	D2-22 nd July	4426	3215	3821
	D3-8 th August	4400	2814	3607

GR-104	D1-8 th July	4665	3269	3967
	D2-22 nd July	5820	3416	4618
	D3-8 th August	4406	2859	3633
Pusa Basmati-1	D1-8 th July	3575	2964	3270
	D2-22 nd July	4655	3281	3968
	D3-8 th August	3074	2920	2997

The grain yields of cv. Narmada in the first date of transplanting (D₁) were 3395 kg ha⁻¹, second date of transplanting (D₂) 4426 kg ha⁻¹ and under third date of transplanting (D₃) 4400 kg ha⁻¹ during the crop season 2007. The corresponding values of yields were 2924, 3215 and 2814 kg ha⁻¹, respectively in 2008. The corresponding pooled values over two years were 3160, 3821 and 3607 kg ha⁻¹, respectively. D₂ transplanting yielded the highest (4426 kg ha⁻¹ in 2007 and 3215) as compared to D₁ and D₃ transplanting. The results of the pooled grain yield over two years were also to be highest (3821kg ha⁻¹) in D₂ transplanting compared with that recorded by the rest of the transplanting.

The grain yields of cv. GR-104 in the first date of transplanting (D₁) were 4665 kg ha⁻¹, second date of transplanting (D₂) 5820 kg ha⁻¹ and under third date of transplanting (D₃) 4406 kg ha⁻¹ during the crop season 2007. The corresponding values of yields were 3269, 3416 and 2859 kg ha⁻¹, respectively in 2008. The corresponding pooled values over two years were 3967, 4618 and 3633 kg ha⁻¹, respectively. D₂ transplanting yielded the highest (5820 kg ha⁻¹ in 2007 and 3416 kg ha⁻¹ in 2008) as compared to D₁ and D₃ transplanting. The results of the pooled grain yield over two years were also to be highest (4618 kg ha⁻¹) in D₂ transplanting compared with that recorded by the rest of the transplanting.

The grain yields of cv. Pusa Basmati-1 in the first date of transplanting (D₁) were 3575 kg ha⁻¹, second date of transplanting (D₂) 4655 kg ha⁻¹ and under third date of transplanting (D₃) 3074 kg ha⁻¹

during the crop season 2007. The corresponding values of yields were 2964, 3281 and 2920 kg ha⁻¹, respectively in 2008. The corresponding pooled values over two years were 3270, 3968 and 2997 kg ha⁻¹, respectively. D₂ transplanting yielded the highest (4655 kg ha⁻¹ in 2007 and 3281 kg ha⁻¹ in 2008) as compared to D₁ and D₃ transplanting. The results of the pooled grain yield over two years were also to be highest (3968 kg ha⁻¹) in D₂ transplanting compared with that recorded by the rest of the transplanting.

After examining the Table 4.2, it was very clear that the crop performed very well in crop season 2007 irrespective of dates of transplanting and genotypes than that of crop season 2008. It might be due to highly conducive weather condition prevailed during crop season 2007 than the crop season 2008 in terms of bright sunshine hours, wind speed, maximum temperature, amount and distribution of rainfall and mean vapour pressure (Table 4.1). The average value of the daily bright sun shine hours were higher (6.4 h) in crop season 2007 than the crop season 2008 (5.8 h) which reflected in higher grain yields of all four cultivars of rice in all three dates of transplanting in crop season 2007 over the crop season 2008. Ramdoss and Subramaniam (1980) reported similar result and documented that the number of sunshine hours had positive effect on grain yield of rice. The higher average daily wind speed (4.7 kmph) might be grain yield reducing factor by affecting the flowering phase of the crop during crop season 2008 than the crop season 2007 (4.4 kmph). Viswambharan *et al.* (1989) reported the similar result and documented that excessive wind speed during flowering and maturation produces high spiklet sterility and low grain yield. The lower maximum temperature and higher mean vapour pressure and rainfall also might be conducive meteorological factors for higher grain yield in all treatments during crop season 2007 over the 2008. Singh *et al.* (1996) reported similar

result during study of influence of agroclimatic elements on the grain yield of the rice. Agrawal *et al.* (1983) reported beneficial effect of humidity (vapour pressure) in general throughout the crop season on grain yield of rice. Bhargava *et al.* (1974) reported that the total rainfall during the crop season was highly correlated positively with yield of paddy. The genotype GR-104 gave the highest yield among the four different cultivars of rice irrespective of dates of transplanting during both the crop seasons as well as on pooled data basis. It might be due to dual effects of higher accumulation of photosynthates in to biomass from higher leaf area index during longer crop duration as well as longer grain filling duration.

The comparison of the results of grain yield during 2007 and 2008 separately as well as pooled basis revealed that differences in yield due to differences in the microenvironment created due to different dates of transplanting. Consistency in the best performance of the second date of transplanting was observed in all the four cultivars of aromatic rice and this was mainly attributed to more congenial weather that prevailed during this period as compared the weather that prevailed during the D₁ and D₃ transplanting. The prevalence of the lowest average maximum temperature in D₂ (31.4°C) during end of anthesis to beginning of grain filling (around 100 DAS) in 2007 (Fig. 4.1a) crop growing season and 30.5 to 31.0°C during same crop phase i.e., around 90 DAS (as early anthesis was recorded in second crop year) during 2008 (Fig. 4.3a) for same transplanting helped in maximizing the grain yield. This result corroborated the findings of the Singh *et al.* (1996). The average minimum temperature in the second date of transplanting during both the years was the lowest viz., 17.5°C in 2007 (Fig. 4.1b) and 23.5°C in 2008 (Fig. 4.3b) in comparison with that which correspondingly prevailed in the treatments D₁ and D₃.

The lowest value of the average maximum temperature throughout the growing season and relatively low values of average minimum temperature during panicle initiation to beginning of grain filling of treatment D₂ proved themselves congenial for higher grain yield. The average mean temperature i.e., 25.9 and 27.4°C in 2007 (Fig. 4.1c) and 2008 (Fig. 4.3c) respectively, was also lower in D₂ in comparison to other date of transplanting during both the crop season. Considerably lower mean temperatures prevailed during the flowering and grain filling stages of the crop grown under D₂ and their beneficial effect was reflected in the grain yield during both the crop year. These results were in good agreement with the findings of Yoshida and Parao (1976) for the grain yield of rice. They reported that the relatively lower temperature during reproductive stage had remarkable effects on increasing spiklet number and hence grain yield. The highest yield of D₂ transplanting might be also due to more or less constant lower mean vapour pressure (Fig. 4.2c and 4.4c) and wind velocity encountered by the same date of transplanting during reproductive phase in both the crop year. These results highly strengthened the findings of the Agrawal *et al.* (1983) and Viswambharan *et al.* (1989) during the study of effects of humidity and wind speed on grain yield, respectively. Munakata (1976) had also reported similar result in the case of rice. Reddy and Reddy (1992) reported similar results and documented that grain yield was negatively correlated with maximum temperature and humidity (vapour pressure) during reproductive phase of the rice crop.

Similar results were reported by Huda *et al.* (1975), Shi and Shen (1990), Samui *et al.* (1996), Singh *et al.* (1996), Samui (1999) and Nigam and Mishra (2003) for rice crop.

4.2.2. Effects on straw yield of rice crop

The results of effects of different dates of transplanting on the straw yield (kg ha^{-1}) have been presented in Table 4.3. The straw yields of cv. Pankhali in the first date of transplanting (D_1) were 11050 kg ha^{-1} , second date of transplanting (D_2) 12746 kg ha^{-1} and under third date of transplanting (D_3) 11523 kg ha^{-1} during the crop season 2007. The corresponding values of yields were 8247, 9568 and 8325 kg ha^{-1} , respectively in 2008.

Table 4.3: Effect of dates of transplanting on straw yield of four different cultivars of rice

Treatments		Straw yield (kg ha^{-1})		
Cultivars	Dates of Transplanting	2007	2008	Pooled
Pankhali	D1-8 th July	11050	8247	9649
	D2-22 nd July	12746	9568	11157
	D3-8 th August	11523	8325	9924
Narmada	D1-8 th July	11570	8859	10215
	D2-22 nd July	12457	10236	11347
	D3-8 th August	11256	8467	9862
GR-104	D1-8 th July	11741	10389	11065
	D2-22 nd July	14268	11265	12767
	D3-8 th August	10569	8955	9762
Pusa Basmati-1	D1-8 th July	9561	9254	9408
	D2-22 nd July	11254	10587	10921
	D3-8 th August	9699	8252	8976

Straw yield in second year were lower than the first year but the trend was alike as that in the first year. The corresponding pooled values over two years were 9649, 11157 and 9924 kg ha^{-1} , respectively. D_2 transplanting yielded the highest (12746 kg ha^{-1} in 2007 and 9568 kg ha^{-1} in 2008) as compared to D_1 and D_3 transplanting. The results of the pooled straw yield over two years were also to be highest (11157 kg ha^{-1}) in D_2 transplanting compared with that recorded by the rest of the transplanting. The straw yields of cv. Narmada in the first date of transplanting (D_1) were 11570 kg ha^{-1} , second date of transplanting (D_2) 12457 kg ha^{-1} and under third date of transplanting (D_3) 11256 kg ha^{-1}

during the crop season 2007. The corresponding values of yields were 8859, 10236 and 8467 kg ha⁻¹, respectively in 2008. Straw yield in second year were lower than the first year but the trend was alike as that in the first year. The corresponding pooled values over two years were 10215, 11347 and 9862 kg ha⁻¹, respectively. D₂ transplanting yielded the highest (12457 kg ha⁻¹ in 2007 and 10236 kg ha⁻¹ in 2008) as compared to D₁ and D₃ transplanting. The results of the pooled straw yield over two years were also to be highest (11347 kg ha⁻¹) in D₂ transplanting.

The straw yields of cv. GR-104 in the first date of transplanting (D₁) were 11741 kg ha⁻¹, second date of transplanting (D₂) 14268 kg ha⁻¹ and under third date of transplanting (D₃) 10569 kg ha⁻¹ during the crop season 2007. The corresponding values of yields were 10389, 11265 and 8955 kg ha⁻¹, respectively in 2008. Straw yield in second year were lower than the first year but the trend was alike as that in the first year. The corresponding pooled values over two years were 11065, 12767 and 9762 kg ha⁻¹, respectively. D₂ transplanting yielded the highest (14268 kg ha⁻¹ in 2007 and 11265 kg ha⁻¹ in 2008) as compared to D₁ and D₃ transplanting. The results of the pooled straw yield over two years were also to be highest (12767 kg ha⁻¹) in D₂ transplanting compared with that recorded by the rest of the transplanting.

The straw yields of cv. Pusa Basmati-1 in the first date of transplanting (D₁) were 9561 kg ha⁻¹, second date of transplanting (D₂) 11254 kg ha⁻¹ and under third date of transplanting (D₃) 9699 kg ha⁻¹ during the crop season 2007. The corresponding values of yields were 9254, 10587 and 8252 kg ha⁻¹, respectively in 2008. Straw yield in second year were lower than the first year but the trend was alike as that in the first year. The corresponding pooled values over two years were 9408, 10921 and 8976 kg ha⁻¹, respectively. D₂ transplanting yielded the highest (11254 kg ha⁻¹ in 2007 and 10587 kg ha⁻¹ in 2008) as compared to D₁ and D₃ transplanting. The results of the pooled straw yield over two years were

also to be highest (10921 kg ha⁻¹) in D₂ transplanting compared with that recorded by the rest of the transplanting.

The above results showed that the genotype GR-104 gave the highest straw yield among the four different cultivars of rice irrespective of dates of transplanting during both the crop seasons as well as on pooled data basis. It might be due to higher accumulation of photosynthates in to dry matter from higher leaf area index.

The overall trend of the straw yield under different dates of transplanting was similar to that of grain yields. The prevalence of lower average maximum temperature through out the crop season along with lower minimum and mean temperature contributed higher straw yield by reducing the maintenance respiration in the second date of transplanting during both the years (Fig. 4.1a to c and 4.3a to c). Although, the crop in D₃ transplanting some times encountered lower average air temperature than that of D₂ transplanting but, the differences were negligible. However, maturity days of all cultivars were more in the D₂ transplanting than that of D₃ for corresponding cultivars during both the years. Kaladevi *et al.* (1999) reported the similar result and documented that the increased lower minimum temperatures resulted in higher dry matter production in rice crop.

4.2.3. Effects on above ground biomass

The above ground biomass production in cv. Pankhali in the first date of transplanting (D₁) were 14125 kg ha⁻¹, second date of transplanting (D₂) 16471 kg ha⁻¹ and under third date of transplanting (D₃) 14948 kg ha⁻¹ during the crop season 2007 (Table 4.4). The corresponding values of yields were 10918, 12688 and 11072 kg ha⁻¹, respectively in 2008. The above ground biomass in second year was lower than the first year but the trend was alike as that in the first year. The corresponding pooled values over two years were 12522, 14580 and 13010 kg ha⁻¹, respectively. D₂ transplanting yielded the highest (16471 kg ha⁻¹ in 2007 and 12688 kg

ha⁻¹ in 2008) as compared to D₁ and D₃ transplanting. The results of the pooled above ground biomass over two years were also to be highest (14580 kg ha⁻¹) in D₂ transplanting compared with that recorded by the rest of the transplanting.

Table 4.4: Effect of dates of transplanting on above ground biomass of four different cultivars of rice

Treatments		Above ground biomass (kg ha ⁻¹)		
Cultivars	Dates of Transplanting	2007	2008	Pooled
Pankhali	D1-8 th July	14125	10918	12522
	D2-22 nd July	16471	12688	14580
	D3-8 th August	14948	11072	13010
Narmada	D1-8 th July	14965	11783	13374
	D2-22 nd July	16882	13451	15167
	D3-8 th August	15656	11270	13463
GR-104	D1-8 th July	16406	13658	15032
	D2-22 nd July	20088	14672	17380
	D3-8 th August	14975	11815	13395
Pusa Basmati-1	D1-8 th July	13136	12218	12677
	D2-22 nd July	15911	13868	14890
	D3-8 th August	12773	11176	11975

The above ground biomass production in cv. Narmada in the first date of transplanting (D₁) were 14965 kg ha⁻¹, second date of transplanting (D₂) 16882 kg ha⁻¹ and under third date of transplanting (D₃) 15656 kg ha⁻¹ during the crop season 2007. The corresponding values of yields were 11783, 13451 and 11270 kg ha⁻¹, respectively in 2008. The above ground biomass production in second year were lower than the first year but the trend was alike as that in the first year. The corresponding pooled values over two years were 13374, 15167 and 13463 kg ha⁻¹, respectively. D₂ transplanting yielded the highest (16882 kg ha⁻¹ in 2007 and 13451 kg ha⁻¹ in 2008) as compared to D₁ and D₃ transplanting. The results of the pooled above ground biomass production over two years were also to be highest

(15167 kg ha⁻¹) in D₂ transplanting compared with that recorded by the rest of the transplanting.

The total above ground biomass production in cv. GR-104 in the first date of transplanting (D₁) were 16406 kg ha⁻¹, second date of transplanting (D₂) 20088 kg ha⁻¹ and under third date of transplanting (D₃) 14975 kg ha⁻¹ during the crop season 2007. The corresponding values of yield were 13658, 14672 and 11815 kg ha⁻¹, respectively in 2008. The above ground biomass production in second year was lower than the first year but the trend was alike as that in the first year. The corresponding pooled values over two years were 15032, 17380 and 13395 kg ha⁻¹, respectively. D₂ transplanting yielded the highest (20088 kg ha⁻¹ in 2007 and 14672 kg ha⁻¹ in 2008) as compared to D₁ and D₃ transplanting. The results of the pooled above ground biomass production over two years were also to be highest (17380 kg ha⁻¹) in D₂ transplanting compared with that recorded by the rest of the transplanting.

The above ground biomass production in cv. Pusa Basmati-1 in the first date of transplanting (D₁) were 13136 kg ha⁻¹, second date of transplanting (D₂) 15911 kg ha⁻¹ and under third date of transplanting (D₃) 12773 kg ha⁻¹ during the crop season 2007. The corresponding values of yields were 12218, 13868 and 11176 kg ha⁻¹, respectively in 2008. The above ground biomass productions in second year were lower than the first year but the trend was alike as that in the first year. The corresponding pooled values over two years were 12677, 14890 and 11975 kg ha⁻¹, respectively. D₂ transplanting yielded the highest (15911 kg ha⁻¹ in 2007 and 13868 kg ha⁻¹ in 2008) as compared to D₁ and D₃ transplanting. The results of the pooled above ground biomass over two years were also to be highest (14890 kg ha⁻¹) in D₂ transplanting compared with that recorded by the rest of the transplanting.

The Table 4.4 clearly showed that the highest above ground biomass productions were recorded by the genotype GR-104 among the

four different cultivars of rice irrespective of dates of transplanting during both the crop seasons as well as on pooled data basis. It might be due to twin effects of longer vegetative phase which accumulated higher photosynthates in to dry matter from higher leaf area index and longer grain filling duration which added the more grain yield.

The overall trend of the above ground biomass production under different dates of transplanting was similar to that of grain as well as straw yields as it was the sum of the grain and straw yields. D₂ transplanting recorded highest above ground biomass production irrespective of cultivars during both the crop years and pooled basis. This result might be due to higher average bright sunshine hours (Fig. 4.2a and 4.4a) encountered by the crop in D₂ transplanting than that of D₁ in crop season 2007 and D₁ and D₃ in 2008 along with other congenial weather conditions which favoured higher grain yield and straw yield. The above ground biomass production in D₃ during 2007 might be off set by the lower crop duration. Munakata (1976) reported similar result for above ground biomass production in rice crop. Singh *et al.* (1996) reported that the yield variation explained by the relative humidity, air temperature and bright sunshine hours. Sarmah and Handique (2001) reported similar results and documented that weekly total rainfall, average weekly maximum temperature, average weekly bright sunshine hours, average weekly morning and evening relative humidity exhibited positive effects on rice yield. Patrohardjono *et al.* (1982) reported close correlation ($r=0.739$) between solar radiation during the ripening phase and the NAR which in turn affected dry matter production in rice crop.

4.2.4. Inferences on the most effective combination of treatments for high yield

It was mentioned earlier that the fundamental objective behind to conduct of this field experiment was to simulate the environmental and varietal effects on growth and yield of various cultivars and also to get the

highest yield for separate cultivar as well as among the cultivars as base yield for further sensitivity analysis of the CERES-Rice model to the various weather and non weather parameters. The data on yield and pertinent yield attributes had indicated that the individual treatment as well as different combinations of the treatments behaved consistently during both the seasons. Thus the task of ascertaining the most effective combination of treatments became quite simple.

Hence, on the basis of the data of two crop season on yield and yield attributes it was ascertained through visual scrutiny that the second date of transplanting (D₂) among all three dates of transplanting for all the four cultivars and genotype GR-104 among all the four aromatic cultivars of rice. viz., Pankhali (P 203), Narmada (Ambica), GR 104 and Pusa Basmati-1 could be reckoned as the optimum condition and high yielding respectively, and were accepted and adopted accordingly.

In the succeeding paragraphs, therefore, the performance of the model has been assessed in respect of individual treatments and described in brief.

4.3. CERES-Rice simulation results

The crop genetic coefficients that influence the occurrence of developmental stages in the CERES-Rice models were derived interactively, by manipulating the relevant coefficients to achieve the best possible match between the simulated and observed number of days to the phenological events using Hunt's method (Hunt *et al.*, 1993). This involved determining the values of the phenology coefficients initially and then the values of the coefficients describing growth and grain development. Minimum crop performance data set are required for those calculations include dates of emergence, anthesis, beginning of grain filling, maturity duration, grain yield, above ground biomass, grain density and weight. The procedure for determining genetic coefficients

involved in running the model using a range of values of each coefficient, in the order indicated above, until the desired level of agreement between simulated and observed values was reached. Iterations for the coefficients were stopped when the agreement reached $\pm 10\%$. For the present study the cultivar genetic coefficients for four cultivars of aromatic rice viz., Pankhali, Narmada, GR 104 and Pusa Basmati-1 (described in experimental details above) had been carried out by trial and error as per Hunt's (Hunt *et al.*, 1993) method. The calibrated genetic coefficients for all above cultivars based on field experimental data of first crop season (Kharif, 2007) at Main Rice Research Station, Nawagam condition are used as mentioned in Table 3.11.

The DSSAT family of CERES-Rice model was employed to simulate growth, development and yield of rice crop for comparison with those respective ones which were observed under field experiment with a view to assess the performance of the model in simulating the results of these characters. The results of simulated yields are described below.

4.3.1. Grain yield

Measured grain yield of rice varied from 3074 (V_4D_3) to 5820 kg ha⁻¹ (V_3D_2) among different cultivars and dates of transplanting during 2007, while model simulated grain yield ranged between 3222 (V_4D_1) to 4887 kg ha⁻¹ (V_3D_2) (Fig. 4.6a to d). The model overestimated the grain yield in D_1 and D_2 treatments while a totally reverse trend was observed in D_3 treatment with $r = 0.86^*$ (Fig. 4.6a) in case of Pankhali cultivar of rice. In case of cv. Narmada, GR-104 and Pusa Basmati-1 (Fig. 4.6b-d) the model underestimated grain yield with $r = 0.96^*$, 0.99^{**} and 0.92^* , respectively starting from D_1 to D_3 . The differences between model simulated and observed grain yield in cv. GR-104 (Fig. 4.6c) were found negligible with a value of $r = 0.99^{**}$. During the crop season of the year 2008, the model overestimated the grain yield in all cultivars irrespective of date of

transplanting (Fig. 4.7a to d). The simulated result given by the model were very poor with $r = 0.67$ in case of cv. Pankhali (Fig. 4.7a). The simulated values of grain yield in respect of cv. Narmada and Pusa Basmati-1 with date of transplanting D₁, D₂ and D₃ which were found in perfect agreement with correspondingly one another with $r = 0.99^{**}$ in both cultivars (Fig. 4.7b and d). However, under the cv. GR-104 simulation performance of the model was very good with $r = 0.97^*$ (Fig. 4.7c). The results of the simulated yield in consequences of the pooled analysis are presented in Fig. 4.8a to d. The results of the simulation performance of the model for grain yield of cv. Pankhali, Narmada and Pusa Basmati-1 were found satisfactory with correlation coefficient values of 0.82^* , 0.95^* and 0.96^* . While the simulated grain yield in case of cv. GR-104 was found in perfect agreement with $r = 0.99^{**}$. Similar results had been obtained by Mall and Aggarwal (2000), Boonjung (2000), Mathews *et al.* (2000) and Rao *et al.* (2002) for rice crop. Jintrawat (1995) also reported reasonably well agreement between simulated and observed grain yield in both photosensitive and insensitive cultivars of rice

Error per cent of CERES-Rice simulated grain yields from those corresponding ones observed during the crop seasons 2007, 2008 and also for the pooled data for both the years are presented in Table 4.5 to 4.7, respectively.

Error percent ranged between 1.5 (V₂D₁) to -16.0 (V₃D₂) during 2007 (Table 4.5). Results for grain yields as simulated by the model under D₂ transplanting of cv. GR-104 on comparison with corresponding observed ones were found to have been under estimated. Simulation performance of the model under rest of all treatments was found satisfactory in case of all four different cultivars of rice.

Table 4.5: Error percent by CERES-Rice simulated grain yield from observed during 2007

Treatments	Error percent*			
	Cultivars			
Dates of Transplanting	Pankhali	Narmada	GR-104	Pusa Basmati-1
D1-8 th July	7.1	1.5	-4.8	-9.9
D2-22 nd July	1.8	-4.1	-16.0	-10.3
D3-8 th August	-3.2	-9.4	-3.7	7.5

*: Error percent= [(Simulated-Observed)/Observed]*100

During crop season 2008 (Table 4.6) error percent ranged between 2.9 (V₂D₂) to 18.0 (V₁D₁). The percent error as recorded in cv. Narmada was lower than those recorded for the rest of the treatments. The model simulated grain yield values were an overestimate in most of the treatments.

Table 4.6: Error percent by CERES-Rice simulated grain yield from observed during 2008

Treatments	Error percent			
	Cultivars			
Dates of Transplanting	Pankhali	Narmada	GR-104	Pusa Basmati-1
D1-8 th July	18.0	6.1	9.8	-4.7
D2-22 nd July	4.5	2.9	11.8	12.0
D3-8 th August	7.2	4.9	16.9	-6.8

The error percentage between the values simulated by CERES-rice model and the corresponding observed ones in pooled results (2007 and 2008) are presented in Table 4.7.

Results showed that error percent ranged between 0.5 (V₄D₃) to 12.1(V₁D₁). Simulation performance of the model was in perfect agreement under all treatments except in V₁D₁ treatment. Saseendran *et al.* (1998a, b) reported similar result for grain yield of jaya and IR 8 cultivars of rice.

Table 4.7: Error percent by CERES-Rice simulated grain yield from observed (pooled of 2007 and 2008)

Treatments	Error percent
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Dates of Transplanting	Cultivars			
	Pankhali	Narmada	GR-104	Pusa Basmati-1
D1-8 th July	12.1	3.6	1.2	-7.5
D2-22 nd July	3.1	-1.2	-5.7	-1.1
D3-8 th August	1.5	-3.8	4.4	0.5

The test criteria for evaluation of model was computed for 2007, 2008 and on a pooled basis and are presented in Table 4.8.

Table 4.8: Test criteria in evaluation of model with respect to grain yield (kg ha⁻¹)

Parameters	2007	2008	Pooled
OMY	4053	3016	3535
Sdo	816	239	505
SMY	3863	3223	3543
SDs	549	344	431
R	0.96**	0.77**	0.94**
Student 't'	0.06971 ^{NS}	0.00799 ^{NS}	0.87033 ^{NS}
MAE	285	264	131
MBE	-191	207	8
RMSE	368	297	166
PE	9.0	9.9	4.7
Index of agreement (D)	0.99	0.98	0.99

where,

OMY: Observed mean yield (kg ha⁻¹)

SMY: Simulated mean yield (kg ha⁻¹)

SDo: Standard deviation of observed

SDs: Standard deviation of simulated

Results showed that measured mean yields were 4053 ± 816 , 3016 ± 239 and 3535 ± 505 during 2007, 2008 and for pooled analysis, while corresponding simulated mean yields were 3863 ± 549 , 3223 ± 344 and 3543 ± 431 , respectively. Positive highly significant association was observed between simulated and observed mean yield values during 2007, 2008 and for the pooled analysis with correlation coefficient values of 0.96** and 0.77** and 0.94** (** - significant at 0.001 level), respectively.

The results of the paired 't' test between simulated and observed grain yield values was found to have been non-significant. The average errors as computed by MAE (mean absolute error) were 285, 264 and 131, while RMSE (Root mean square error) were recorded as 368, 297 and 166 during 2007, 2008 and for pooled analysis, respectively. Lower MAE and RMSE were recorded during 2008 growing season where as they were lowest on pooled basis. Mean bias error (MBE) described the direction of the error bias. It was found lowest on pooled basis followed by 2007 crop growing year. The negative sign suggested the underestimation of the grain yield by the model. Index of agreement (D) for both the years and for pooled data ranged between 0.98 to 0.99. The evaluation of the model on an overall basis revealed that the simulation performance of the model in respect of grain yield was found perfect on pooled basis than in any other period.

Although, simulated grain yields by the model were vary close with the observed grain yield for different dates of transplanting of various cultivars of rice, but some variations in estimation in grain yield as simulated by model viz. -16.0 (V₃D₂) in 2007 and 18.0 (V₁D₁), 16.9 (V₃D₃) and 12.0 (V₄D₂) in 2008 were found. It was difficult to pin point the precise reasons for this deviation as DSSAT CERES-Rice is a mechanistic crop growth simulation model capturing the complex effect of climate, genotype and agronomic variable through several functions. Perhaps, such a variation could be intrinsic to the model. Timsina *et al.* (1995) reported simulated grain yield of Pant 4 were within 1 to 15 % of observed yields. Similar result had recorded by Seino (1995) for comparing the simulate and observed yield of rice crop.

4.3.2. Above ground biomass

Measured above ground biomass of various cultivars of rice ranged between 12773 (V₄D₃) to 20088 kg ha⁻¹ (V₃D₂) among different

dates of transplanting during the crop growing season of 2007, while model simulated dry matter ranged between 11453 (V₄D₁) to 16815 kg ha⁻¹ (V₂D₂) (Fig. 4.9). The model underestimated the biomass production in all the treatments of cv. Pusa Basmati-1, D₁ transplanting of cv. Pankhali, D₂ and D₃ transplanting of cv. Narmada as well as GR-104, while rest of others recorded overestimation by the model during 2007; however, the trend of simulated values was similar to that of observed values and their correlation coefficients (between the simulated and observed) values were 0.96*, 0.85*, 0.96* and 0.95* (* - significant at 0.05 level) in the cv. Pankhali, Narmada, GR-104 and Pusa Basmati-1, respectively. The performance of the model in simulating the above ground biomass of cv. Narmada was poorer than that for the rest of cultivars of rice with significant association between simulated and observed values at 0.05 levels. The trend of simulated values of above ground biomass production was observed to be similar to the corresponding trend for simulated grain yield except in case of treatment combinations V₄D₁ and V₂D₂.

In case of the second year crop season, measured above ground biomass production ranged between 11072 (V₁D₃) to 14672 kg ha⁻¹ (V₃D₂), while the simulated biomass varied between 10310 (V₄D₃) to 16714 kg ha⁻¹ (V₃D₂) (Fig. 4.10). In all the dates of transplanting of various cultivars of rice, model overestimated simulated biomass except in V₄D₁ and V₄D₃. However, the results of the treatments were found significant with correlation coefficient of 0.99** in cv. Narmada and Pusa Basmati-1 and 0.97* in cv. GR-104, respectively. Where as result of cv. Pankhali was found non significant with $r = 0.77$. The trends of simulated values also matched with that of measured ones. The results obtained for corresponding grain yields were very similar. Tongyai (1994) reported similar result for grain and biomass yield of rice crop in Bangkok.

The results of the analysis of the pooled data (average of 2007 and 2008) as presented in Fig. 4.11 revealed that measured biomass ranged between 11975 (V₄D₃) to 17380 kg ha⁻¹ (V₃D₂), while the model simulated biomass yields varied between 11226 (V₄D₃) to 16702 kg ha⁻¹ (V₃D₂). In all the dates of transplanting of various cultivars of rice, model overestimated biomass except in V₃D₂, V₄D₁ and V₄D₃. However, there seemed to exist significant association between the simulated and measured values with 'r' values of 0.99* for all four cultivars of rice. The magnitude of variation between the simulated and measured values was least in cv. Pusa Basmati-1 where as cv. Pankhali recorded highest variation. The model simulated the biomass production under treatment D₂ of cv. Pusa Basmati-1 quite satisfactory in comparison with prediction under the rest of the treatments. The trend of simulated values of the above ground biomass yield was similar to that for the corresponding grain yield under all the dates of transplanting of all four different cultivars of aromatic rice.

The error per cent for CERES-Rice simulated biomass production observed during the crop season 2007, 2008 and for pooled data are presented in Table 4.9 to 4.11.

Error percent ranged between 0.2 (V₃D₃) to -16.9 (V₄D₁) during crop season 2007 (Table 4.9). Model underestimated the above ground biomass production in all the treatments except V₁D₂, V₁D₃, V₂D₁ and V₂D₃. Lowest percent error was recorded in D₃ transplanting of cv. GR-104. D₃ transplanting recorded lowest error percent in the case of all the cultivars except in cv. Narmada where D₂ recorded lowest error percent.

Table 4.9: Error percent by CERES-Rice simulated above ground biomass from observed during 2007

Treatments	Error percent			
	Cultivars			
Dates of Transplanting	Pankhali	Narmada	GR-104	Pusa

				Basmati-1
D1-8th July	-6.4	7.1	-3.2	-12.8
D2-22nd July	5.8	-0.4	-16.9	-8.6
D3-8th August	5.3	1.2	0.2	-4.9

Error percent ranged between -3.0 (V_4D_1) to 22.6 (V_1D_1) during crop season 2008. The percent error were almost reverse during second year to that revealed in the first year and model overestimated the above biomass yield under all the dates of transplanting of all four cultivars except under treatments V_4D_1 and V_4D_3 (Table 4.10). Simulation performance of cv. Narmada irrespective of the date of transplanting was found better than that for the rest of the genotypes of aromatic rice.

Table 4.10: Error percent by CERES-Rice simulated above ground biomass from observed during 2008

Treatments	Error percent			
	Cultivars			
Dates of Transplanting	Pankhali	Narmada	GR-104	Pusa Basmati-1
D1-8th July	22.6	6.8	11.9	-3.0
D2-22nd July	14.2	8.3	13.9	13.9
D3-8th August	6.9	10.1	20.2	-7.7

The error percent varied between 1.9 (V_4D_2) to 9.5 (V_1D_2) under pooled results (Table 4.11). Here also the trend of the simulation values was similar to the trend that was followed by observed values in the year 2008. The model overestimated the above biomass production under all the treatment combinations except in V_3D_2 , V_4D_1 and V_4D_3 .

Table 4.11: Error percent by CERES-Rice simulated above ground biomass from observed (pooled of 2007 and 2008)

Treatments	Error percent			
	Cultivars			
Dates of Transplanting	Pankhali	Narmada	GR-104	Pusa Basmati-1
D1-8th July	6.2	7.0	3.6	-8.1
D2-22nd July	9.5	3.5	-3.9	1.9

D3-8th August	6.0	4.9	9.0	-6.3
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The various test criteria for evaluation of model were computed for 2007, 2008 and for pooled data and the results are presented in Table 4.12. Results showed that mean measured yields of above ground biomass production were 15528 ± 1923 , 12382 ± 1264 and 13955 ± 1508 during 2007, 2008 and for pooled data, while corresponding simulated biomass yields were 15065 ± 1888 , 13619 ± 1881 and 14342 ± 1669 , respectively. Deviation was less in simulated results as compared to that in observed yield of biomass yield in 2007, where as it was more in 2008 and pooled basis. Positive significant association was observed between simulated and observed biomass production during 2007, 2008 and for pooled data with correlation coefficient values of 0.78** and 0.85** and 0.88** respectively.

Table 4.12: Test criteria in evaluation of model with respect to above ground biomass

Parameters	2007	2008	Pooled
OMY	15528	12382	13955
Sdo	1923	1264	1508
SMY	15065	13619	14342
SDs	1888	1881	1669
R	0.78**	0.85**	0.88**
Student 't'	0.23441 ^{NS}	0.00168 ^{NS}	0.11705 ^{NS}
MAE	968	1442	795
MBE	-464	1237	387
RMSE	1307	1587	847
PE	8.4	12.8	6.0
Index of agreement (D)	0.98	0.99	0.99

The results of the grain yields during the corresponding period also displayed similar behaviour. Non-significant differences were observed between simulated and observed biomass production in terms of paired 't' test. The average errors as computed by MAE were 968, 1442 and 795, while RMSE values recorded were 1307, 1587 and 847 during 2007, 2008 and for pooled data, respectively. MBE was lowest on pooled

basis. Lowest index of agreement (D) recorded was 0.98 in 2007 crop growing season.

The overall trend of simulated above ground biomass production indicated overestimation by the model except for few treatments but error percent remained lower than 9.5 on pooled basis. Salam *et al.* (2003) also documented that the agreement between observed and simulated final biomass was not very satisfactory in rice crop and suggested that growth and biomass routines need to be revised and refined. Similar result was also reported by the Kropff *et al.* (1994) for same crop.

The equation used in CERES-Rice model for biomass production includes IPAR (Intercepted photosynthetically active radiation) and LAI (Leaf area index). The overestimation of the biomass by the model could be due to the overestimation of leaf area index. The functional form of LAI simulation needed to be revised. However, in the present investigation this has not been attempted, but could be tried in future studies.

4.3.3. Periodic dry matter production

The periodic dry matter productions (kg ha^{-1}) as observed and simulated by the model under different dates of transplanting during 2007, 2008 and in respect of pooled data are presented in Fig. 4.12 to 4.14 respectively. Results showed that simulated periodic dry matter production during different phenological stages as (E: emergence, EJ: end of juvenile phase, PI: panicle initiation, AN: anthesis, BGF: beginning of grain filling and PM: physiological maturity) when compared with the corresponding measured ones under different dates of transplanting of various cultivars of rice from nursery stage were found to have been overestimated by the model during nursery phase irrespective of cultivars and date of transplanting. The model underestimated the periodical dry matter under D₁ transplanting and thereafter overestimated by the model

in case of cv. Pankhali during crop season of 2007 (Fig. 4.12a). However the trend of the simulated values was similar to that of the measured ones and the extent of variation was quite pronounced from very beginning of crop stage to the maturity stage. Similar trend was observed for above ground biomass production for corresponding period.

The trend of the simulated values as observed under D₁ and D₂ transplanting of cv. Narmada was reversed that of cv. Pankhali during 2007, where as it was similar in case of D₃ transplanting. But the variation between measured and simulated values was less. Simulation performance of the model in respect of the periodic dry matter production in case of treatment D₂ in the year 2007 (Fig. 4.12b) was such that the simulated values were almost identical with the corresponding observed values after nursery phase up to physiological maturity stage and the performance could be reckoned as better when compared with that in case of the rest of the transplanting.

The model underestimated the periodical dry matter under D₁ and D₂ transplanting of cv. GR-104 where as it was overestimated in case of D₃ transplanting during 2007, but extent of variation was quite negligible (Fig. 4.12c). However the trend of the simulated values of periodical dry matter was similar to that of the measured ones.

The model underestimated the periodical dry matter irrespective of dates of transplanting in case of cv. Pusa Basmati-1 (Fig. 4.12d) during 2007. However the trend of the simulated values of periodical dry matter was similar to that of the measured ones. Similar trend was also observed for above ground biomass production for corresponding period.

During the second year (Fig. 4.13a to d) the results of simulation by the model were almost reversed to those observed in 2007 and model overestimated the periodical dry matter irrespective of genotypes and dates of transplanting except in D₁ and D₃ transplanting of cv. Pusa

Basmati-1, but simulated values were in close agreement with the corresponding observed ones. The performance of the model in estimation of the periodical dry matter production was poor, hence the agreement was poor than that observed during 2007. There was no definite trend found for variation between simulated and observed dry matter values from D₁ to D₃ transplanting. The pattern of values as simulated by the model on the basis of pooled data for various genotypes and treatments D₁, D₂ and D₃ (Fig. 4.14 a to d) was more similar to that observed in case of these treatments in 2008 than that of 2007. Here the variation between the simulated values and the corresponding observed ones was less than that observed under separately on year wise basis D₁ and D₂ on the basis of pooled data.

The overall trend of the simulated values of dry matter at different stages was similar to that of those correspondingly observed values. On an overall basis the model simulated values of periodic dry matter were more than corresponding those observed except in few cases. Similar results were reported by the Buresh *et al.* (1988a, b) and John *et al.* (1989a, b). The degree of variation in estimation of dry matter was less in case of D₂ transplanting in all genotypes except cv. Pankhali. On the basis of simulated values of periodic dry matter production based on pooled data it was observed that the model performed better in case of treatment D₂ than it did in case of treatment D₁ and D₃.

4.3.4. Phenological development

The accurate simulation of phasic development of a crop is crucial for accurate simulation of crop growth and yield. Thus, evaluation of the phasic development is the most important and the first step in any study aimed at assessment of the performance of a simulation crop model.

4.3.4.1. Days to anthesis

An effort was made to predict the days to anthesis and maturity for different treatments and the results of predictions were evaluated with respect to the observed duration in days. The observed duration of days to anthesis varied between 93 (V₄D₃) to 107 (V₃D₁) day and that simulated by CERES-Rice model from 91 (V₁D₃ and V₄D₃) to 104 (V₃D₁) day during the crop-growing season of the year 2007 (Fig. 4.15a). Similarly the observed variation in days to anthesis ranged between 91 (V₄D₃) to 98 (V₃D₁) day and that simulated values from 93 (V₂D₃) to 103 (V₃D₁ and V₃D₂) for the year 2008. The observed variation in days to anthesis varied between 92.0 (V₂D₃ and V₄D₃) to 102.5 (V₃D₁) day in case of the pooled data. The corresponding variation in values simulated by the model ranged between 92.5 (V₁D₃) to 103.5 (V₃D₁) (Fig. 4.15 b, c).

The values of error percent in the model simulated days to anthesis from their correspondingly observed values in various genotypes of rice during 2007, 2008 and for pooled data are presented in Table 4.13 to 4.15, respectively. The range of magnitude of deviation between simulated and observed days to anthesis varied between 0 to 3 d in various treatments during crop season 2007.

Table 4.13: Error percent by CERES-Rice simulated days to anthesis from observed during 2007

Treatment	Observed	Simulated	Deviation	Error %
V ₁ D ₁	98	100	2	2.0
V ₁ D ₂	96	96	0	0.0
V ₁ D ₃	94	91	-3	-3.2
V ₂ D ₁	99	98	-1	-1.0
V ₂ D ₂	96	97	1	1.0
V ₂ D ₃	94	93	-1	-1.1
V ₃ D ₁	107	105	-2	-1.9
V ₃ D ₂	103	103	0	0.0
V ₃ D ₃	97	94	-3	-3.1
V ₄ D ₁	98	96	-2	-2.0
V ₄ D ₂	95	95	0	0.0
V ₄ D ₃	93	92	-1	-1.1

The highest magnitude of error per cent of deviation between simulated and observed days to anthesis was recorded as 3.2% in V₁D₃. However, D₂ transplanting recorded perfect agreement between simulated and observed days to thesis in all genotypes of rice except cv. Narmada (Table 4.13). This was due to the fact that under D₂ transplanting the crop encountered favourable and congenial weather conditions when compared with the weather conditions encountered under D₁ and D₃ transplanting.

The range of magnitude of deviation between simulated and observed days to anthesis varied between 1 to 6 d in various treatments during crop season 2008. The highest magnitude of error per cent of deviation between simulated and observed days to anthesis was recorded as 6.2% in V₃D₂ where as, treatments V₄D₁ recorded lowest magnitude of error per cent between simulated and observed days to anthesis (Table 4.14).

The range of magnitude of deviation between simulated and observed days to anthesis varied between 0.5 to 3.0 d in various treatments on pooled data on days to anthesis of crop season 2007 and 2008.

Table 4.14: Error percent by CERES-Rice simulated days to anthesis from observed during 2008

Treatment	Observed	Simulated	Deviation	Error %
V ₁ D ₁	95	99	4	4.2
V ₁ D ₂	93	96	3	3.2
V ₁ D ₃	92	90	2	2.2
V ₂ D ₁	96	93	2	2.1
V ₂ D ₂	94	90	1	1.1
V ₂ D ₃	90	93	3	3.3
V ₃ D ₁	98	103	5	5.1
V ₃ D ₂	97	103	6	6.2
V ₃ D ₃	95	97	2	2.1
V ₄ D ₁	97	98	1	1.0

V₄D₂	95	98	3	3.2
V₄D₃	91	95	4	4.4

The highest magnitude of error per cent of deviation between simulated and observed days to anthesis was recorded as 3.1% in V₁D₁ where as, treatment lowest magnitude of error per cent between simulated and observed days to anthesis were recorded by V₁D₃, V₂D₁, V₃D₃, V₄D₁ (Table 4.15).

Table 4.15: Error percent by CERES-Rice simulated days to anthesis from observed in case of pooled data (2007 and 2008)

Treatment	Observed	Simulated	Deviation	Error %
V₁D₁	96.5	99.5	3.0	3.1
V₁D₂	94.5	96.0	1.5	1.6
V₁D₃	93.0	92.5	-0.5	-0.5
V₂D₁	97.5	98.0	0.5	0.5
V₂D₂	95.0	96.0	1.0	1.1
V₂D₃	92.0	93.0	1.0	1.1
V₃D₁	102.5	104.0	1.5	1.5
V₃D₂	100.0	103.0	3.0	3.0
V₃D₃	96.0	95.5	-0.5	-0.5
V₄D₁	97.5	97.0	-0.5	-0.5
V₄D₂	95.0	96.5	1.5	1.6
V₄D₃	92.0	93.5	1.5	1.6

After examining the Tables 4.13 to 4.15 this could be inferred that the performance of CERES-Rice model in terms of simulated days to anthesis was more satisfactory in 2007 than in 2008 and also in pooled data.

Table 4.16: Mean error percent by CERES-Rice simulated days to anthesis in various genotypes of rice during 2007, 2008 and pooled data (2007 and 2008)

Genotypes	Mean error per cent		
	2007	2008	Pooled
Pankhali	-0.38	3.20	1.39

Narmada	-0.34	2.16	0.85
GR-104	-1.65	4.46	1.31
Pusa Basmati-1	-1.04	2.86	0.91

The range of mean error percents of days to anthesis (mean of three dates of transplanting) for individual genotype of rice were recorded as - 0.34 to -1.65 %, 2.16 to 4.46% and 0.85 to 1.39 % during 2007, 2008 and pooled data, respectively (Table 4.16). The results showed that the model underestimated the days to anthesis in crop season 2007 irrespective of cultivars where as, it was overestimated during 2008 and pooled basis by the model. The results also showed that more or less genotype GR-104 recorded highest mean error percent among four different cultivars of aromatic rice in terms of days to anthesis where as, cv. Narmada recorded the least mean error percent.

The results of various test criteria used for evaluation of model with respect to days to anthesis for 2007, 2008 and for pooled data were calculated and are presented in Table 4.17.

Table 4.17: Test criteria for evaluation of the model with respect to simulation of days to anthesis in rice

Parameters	2007	2008	Pooled
OMY	97.5	94.4	96.0
SDo	4.0	2.5	3.1
SMY	96.7	96.3	97.0
SDs	4.3	4.3	3.6
r	0.93**	0.68*	0.95**
Student 't'	0.08541 ^{NS}	0.07381 ^{NS}	0.00975 ^{NS}
MAE	1.33	3.33	1.33
MBE	0.83	1.83	1.08
RMSE	1.68	3.58	1.58
PE	1.73	3.80	1.65
Index of agreement (D)	0.98	0.96	0.99

Results showed that mean measured days to anthesis were 97.5 ± 4.0 , 94.4 ± 2.5 and 96.0 ± 3.1 during 2007, 2008 and for pooled data, while corresponding simulated days to anthesis were 96.7 ± 4.3 , 96.3 ± 4.3 and 97.0 ± 3.6 , respectively (Table 4.17). The values of errors as computed in terms of MAE, MBE, RMSE and percent errors showed that model performed well in 2007 than in the other period. Deviations were higher in simulated results as compared to that in observed days to anthesis in 2007, 2008 and pooled data basis. Highly positive significant association was observed between simulated and observed days to anthesis during 2007 and for pooled data with correlation coefficient values of 0.93** and 0.95** respectively. Although, low but significant correlation coefficient (0.68*) was recorded during 2008. However, non-significant differences were observed between simulated and observed days to anthesis in terms of paired 't' test. This result was in good agreement with the finding of Timsina *et al.* (1995) for validation of days to anthesis using CERES-Rice model. Saseendran *et al.* (1998a, b) also reported better prediction of days to anthesis in jaya and IR 8 cultivars of rice.

The overall results showed that days to anthesis decreased date wise irrespective of cultivars from first to third date of transplanting, both in case of observed and simulated values. This decreasing trend could be explained in terms of the rate of development (inverse of duration) as related to temperature and photoperiod (Marcellos and Single, 1971 and Saini *et al.*, 1986) as expressed by the relation

$$D (\text{day}^{-1}) = a + bt + cP.$$

where,

- D = Development rate
- t = Mean temperature (°C)
- P = Photoperiod (h)
- a, b and c = Empirical constants.

Prevalence of low values of maximum, minimum and mean temperature as well as photoperiod in case of first transplanting date for longer duration (during 60 to 90 DAS) and reverse of it in the case of succeeding transplanting date as depicted in Fig. 4.1 and Fig. 4.3 was evident from the figure and seemed to have contributed to this finding regarding the trend in days to anthesis. Thus, the prolonged period of favourable temperature and lower photoperiod in addition to higher mean vapour pressure resulted in relatively more duration of days to anthesis under D₁ transplanting followed by D₂ and D₃.

4.3.4.2. Days to maturity

The observed duration of days to maturity varied between 124 (V₄D₃) to 140 d (V₃D₁), 123 (V₂D₃ and V₄D₃) to 135 d (V₃D₁) and 123.5 (V₄D₃) to 137.5 d (V₃D₁) during 2007, 2008 and for results of pooled data, respectively (Fig. 4.16 a to c). Similarly the corresponding values as the simulated by the model ranged between 124 (V₂D₃) to 137 d (V₁D₁), 121 (V₂D₃) to 139 d (V₁D₁) and 124.5 d (V₂D₃) to 137.5 d (V₁D₁), respectively. Days to maturity as simulated by the model were found to have been underestimated on comparison with correspondingly by observed ones irrespective of cultivars during crop year 2007. In case of first crop growing season the model simulated days to maturity underestimated the actual ones in the range between -2.0 to -5.0 d except in V₁D₁, V₁D₂ and V₄D₃ (Table 4.18).

Table 4.18: Error percent in model simulated days to maturity from their observed in rice during 2007

Treatment	Observed	Simulated	Deviation	Error %
V ₁ D ₁	135	137	2	1.5
V ₁ D ₂	134	135	1	0.7
V ₁ D ₃	130	128	-2	-1.5
V ₂ D ₁	137	134	-3	-2.2
V ₂ D ₂	136	131	-5	-3.7

V ₂ D ₃	127	124	-3	-2.4
V ₃ D ₁	140	136	-4	-2.9
V ₃ D ₂	139	135	-4	-2.9
V ₃ D ₃	132	129	-3	-2.3
V ₄ D ₁	135	131	-4	-3.0
V ₄ D ₂	134	129	-5	-3.7
V ₄ D ₃	124	128	4	3.2

The range of magnitude of deviation between simulated and observed days to maturity varied between 1 to 5 d in various treatments during crop season 2007. The highest magnitude of error per cent of deviation between simulated and observed days to maturity was recorded as 3.7% in V₂D₂ and V₄D₂. However, V₁D₂ treatment recorded near perfect agreement between simulated and observed days to maturity (Table 4.18).

In the matter of simulating the days to maturity, the model overestimated the days to maturity in all the treatments except V₄D₁ and V₄D₃ and the overestimation ranged from 1 to 11 d during crop season 2008. This overestimation was found to have an increasing trend from D₁ to D₃ transplanting in all genotypes (Table 4.19).

Table 4.19: Error percent in model simulated days to maturity from their observed in rice during 2008

Treatment	Observed	Simulated	Deviation	Error %
V ₁ D ₁	132	135	3	2.3
V ₁ D ₂	130	133	3	2.3
V ₁ D ₃	126	132	6	4.8
V ₂ D ₁	134	137	3	2.2
V ₂ D ₂	133	137	4	3.0
V ₂ D ₃	123	134	11	8.9
V ₃ D ₁	135	139	4	3.0
V ₃ D ₂	134	138	4	3.0
V ₃ D ₃	126	134	8	6.3
V ₄ D ₁	134	133	-1	-0.7
V ₄ D ₂	132	133	1	0.8
V ₄ D ₃	123	121	-2	-1.6

The range of magnitude of deviation between simulated and observed days to maturity varied between 0.0 to 4.0 d in various treatments on pooled data on days to maturity of crop season 2007 and 2008 (Table 4.20).

Table 4.20: Error percent in model simulated days to maturity from their observed in rice on the basis of pooled data (2007 and 2008)

Treatment	Observed	Simulated	Deviation	Error %
V₁D₁	133.5	136.0	2.5	1.9
V₁D₂	132.0	134.0	2.0	1.5
V₁D₃	128.0	130.0	2.0	1.6
V₂D₁	135.5	135.5	0.0	0.0
V₂D₂	134.5	134.0	-0.5	-0.4
V₂D₃	125.0	129.0	4.0	3.2
V₃D₁	137.5	137.5	0.0	0.0
V₃D₂	136.5	136.5	0.0	0.0
V₃D₃	129.0	131.5	2.5	1.9
V₄D₁	134.5	132.0	-2.5	-1.9
V₄D₂	133.0	131.0	-2.0	-1.5
V₄D₃	123.5	124.5	1.0	0.8

The highest magnitude of error per cent of deviation between simulated and observed days to maturity was recorded as 3.2% in V₃D₃ where as, perfect agreements between simulated and observed days to maturity were recorded by the treatments V₂D₁, V₃D₁ and V₃D₂ (Table 4.20).

The range of mean error percents of days to maturity (mean of three dates of transplanting) for individual genotype of rice were recorded as 0.23 to -2.74 %, -0.54 to 4.73 % and 0.65 to 1.65 % during 2007, 2008 and pooled data, respectively (Table 4.21). The results showed that the model underestimated the days to maturity in almost all genotypes of rice in crop season 2007 where as, it was overestimated in all genotypes of

rice except Pusa Basmati-1 during 2008 and pooled basis by the model. This result highly strengthened the finding of 0 to 4 days deviation between simulated and observed days to maturity using CERES-Rice model by Alocilja and Richie (1991). Timsina *et al.* (1998) also reported similar result for validation of days to maturity in rice. Similar result was found by Seino (1995) during evaluation of the CERES-rice model for days to maturity.

Table 4.21: Mean error percent by CERES-Rice simulated days to maturity in various genotypes of rice during 2007, 2008 and pooled data (2007 and 2008)

Genotypes	Mean error per cent		
	2007	2008	Pooled
Pankhali	0.23	3.11	1.65
Narmada	-2.74	4.73	0.94
GR-104	-2.67	4.10	0.65
Pusa Basmati-1	-1.16	-0.54	-0.85

The results on various test criteria used for evaluation of the performance of the model with respect to days to maturity are presented in Table 4.22.

Table 4.22: Test criteria in evaluation of model with respect to days to physiological maturity

Parameters	2007	2008	Pooled
OMY	133.58	130.17	131.88
Sdo	4.70	4.47	4.58
SMY	131.42	133.83	132.63
SDs	3.99	4.63	4.31
R	0.79**	0.69*	0.74**
Student 't'	0.02595 ^{NS}	0.00454 ^{NS}	0.01525 ^{NS}
MAE	3.33	4.17	3.75
MBE	-2.17	3.67	0.75
RMSE	3.54	5.02	4.28
PE	2.65	3.85	3.25
Index of agreement (D)	0.98	0.98	0.98

The trend of correlation coefficient 't' test, mean absolute error, root mean square error and degree of agreement were observed to be the same as observed for days to anthesis. CERES-Rice model performance in terms of simulated days to maturity was found superior in 2007 to that in 2008 and also in case of pooled data. Tongyai (1994) also reported reasonable agreement between simulated and observed days to maturity with RMSE= 4.8 and SE= 4.6 d for a range of varieties.

4.3.4.3. Periodic leaf area index

The CERES-Rice simulated leaf area index was compared with the corresponding actual field observations of LAI taken at different phenological phases of the crop for all the treatments under study. The results are depicted in Fig. 4.17 to 4.19. The measured as well as model simulated LAI was found maximum at the anthesis stage during both the years. Slightly low peak in LAI both in simulated and observed values was noticed at BGF (Beginning of grain filling) due to additive effect of senescence of lower leaves started and vegetative growth had ceased at that stage. The values of LAI for various genotypes of rice were highest in D₂ transplanting and lowest in D₃ under measured as well as simulated conditions during both the years. This was reflected in getting higher grain as well as above ground biomass yield.

The highest LAI was recorded in GR-104 in all the corresponding dates of transplanting than that of others. The observed values of LAI in case of D₂ transplanting were 2.5, 3.5, 4.0 and 3.3 for genotypes Pankhali, Narmada, GR-104 and Pusa Basmati-1 respectively in 2007, while they were 2.4, 3.1, 3.8 and 2.9 respectively for corresponding genotypes in 2008. The plants with high LAI intercepted maximum solar radiation, which was vital for photosynthetic activity of the leaves. In cereals, under most circumstances, majority of the carbohydrates in the grain are derived from carbon dioxide fixation (photosynthesis) after flowering

stage. This was the reason for higher grain yield in respect of D₂ transplanting treatments of all four genotypes of rice. Similar observations have been made by Evans (1975).

The CERES-Rice model underestimated the LAI from emergence to maturity in all four genotypes and dates of transplanting except at few points during 2007 and also under pooled data, where as model overestimated the LAI during crop season 2008 (Fig. 4.17 to 4.19). The observed LAI was higher in the crop season 2007 was might be due to congenial weather favoured optimum leaf expansion. This was the tangible reason for underestimation and overestimation of above ground biomass production during 2007 and 2008 respectively (Fig. 4.9 to 4.11).

Table 4.23: Error percent by CERES-Rice simulated maximum leaf area index from observed during 2007

Treatments	Error percent			
	Cultivars			
Dates of Transplanting	Pankhali	Narmada	GR-104	Pusa Basmati-1
D1-8 th July	-9.6	4.7	-16.2	-7.5
D2-22 nd July	4.3	-7.1	-18.0	-17.5
D3-8 th August	2.8	-24.4	-16.1	-8.5

The error percentage between simulated leaf area index by the model and the corresponding observed ones in crop year 2007, 2008 and pooled basis are presented in Table 4.23 to 4.25. The range of error percent between simulated LAI and observed ones varied between 2.8 to 24.4% in crop season 2007 (Table 4.23). The corresponding values were 2.4 to 24.7% (Table 4.24) and 0.6 to 14.2% (Table 4.25) in crop season 2008 and pooled basis, respectively. Mall and Aggarwal (2002) also reported good agreement between simulated and observed values (using CERES-Rice and ORYZA 1N) for the general pattern of LAI over the growing season.

Table 4.24: Error percent by CERES-Rice simulated maximum leaf area index from observed during 2008

Treatments	Error percent			
	Cultivars			
Dates of Transplanting	Pankhali	Narmada	GR-104	Pusa Basmati-1
D1-8 th July	15.0	16.7	16.9	9.8
D2-22 nd July	24.7	5.2	10.4	10.9
D3-8 th August	17.1	2.4	-11.3	5.9

The over all results showed that the LAI was underestimated by the model during crop season 2007 irrespective of cultivars and dates of transplanting except in three cases where as, it was overestimated by the model during 2008 except treatment V₃D₃.

Table 4.25: Error percent by CERES-Rice simulated maximum leaf area index from observed (Pooled of 2007 and 2008)

Treatments	Error percent			
	Cultivars			
Dates of Transplanting	Pankhali	Narmada	GR-104	Pusa Basmati-1
D1-8 th July	1.7	10.5	-2.6	0.6
D2-22 nd July	14.2	-1.4	-4.2	-4.0
D3-8 th August	9.8	-12.3	-14.1	-1.5

The performance of the model in simulating the LAI on pooled basis was good as magnitudes of error percent remain lower than 12.0% in most of the cases. Genotype Pankhali recorded more or less highest error per cent irrespective of dates of transplanting. However, there was no definite trend in terms of error per cent was found among the dates of transplanting in all the four cultivars of aromatic rice.

Table 4.26: Test criteria in evaluation of model with respect to maximum leaf area index

Parameters	2007	2008	Pooled
OMY	3.07	2.65	2.86
Sdo	0.66	0.49	0.55
SMY	2.74	2.92	2.83
SDs	0.48	0.56	0.49

R	0.88**	0.91**	0.90**
Student 't'	0.00583 ^{NS}	0.00246 ^{NS}	0.68637 ^{NS}
MAE	0.38	0.32	0.18
MBE	-0.32	0.27	-0.03
RMSE	0.45	0.35	0.23
PE	14.7	13.2	7.99
Index of agreement (D)	0.98	0.98	0.98

The results of various test criteria used for evaluation of model with respect to maximum leaf area index for 2007, 2008 and for pooled data were calculated and are presented in Table 4.26. The values of RMSE for observed and simulated maximum LAI were 0.45, 0.35 and 0.23 for 2007, 2008 and for pooled data, respectively (Table 4.26).

The above values suggested that performance of the model was better in 2008 than that in 2007 and also for pooled data. Mean observed and mean simulated standard deviation were also recorded as 0.66, 0.49, 0.55 and 0.48, 0.56 and 0.049 with $r = 0.88^{**}$, 0.91^{**} and 0.90^{**} for 2007, 2008 and for the pooled results, respectively. On the basis of these values, the performance of the model was found better than that at any other time. Mean bias error remained -0.32, 0.27 and -0.03 for corresponding periods, and they suggested consistent underestimation of LAI except in 2008. The simulated LAI values vary from one another under different dates of transplanting as well as from genotypes to genotype (Fig. 4.17 to 4.19). This differential behaviour of the model showed that the function of LAI simulation in the CERES-rice model needed to be modified for the improvement of the performance of CERES-Rice model.

4.3.4.4. Number of grains per square meter

The association between observed and simulated grains number per square meter in crop season 2007, 2008 and for pooled data are presented in Fig. 4.20 a to c, respectively. The results showed that measured grain per meter square (GPMS) was 16653 ± 2676 , while simulated value remained at 16119 ± 2852 during 2007 (Table 4.27).

Simulated GPMS values were found to have been underestimated by the model when compared with the corresponding observed ones in most of the cases except under a few ones during 2007 and pooled data basis, where as model overestimated the GPMS during 2008 except in three treatments. Paired-'t' test between simulated and observed values showed that the differences were non-significant, but the correlation coefficient between observed and simulated values found significant both in 2007 and 2008 as well as pooled basis. Mean absolute error, mean bias error, root mean square error and the index of agreement between simulated and observed values were 850, -535, 1101 and 0.99 respectively, which were lower for 2007 than respectively those for 2008 and for pooled data. The results suggested that performance of the model in simulating GPMS for the crop-growing season of 2008 was poor.

Table 4.27: Test criteria in evaluation of model with respect to grain numbers per square meter

Parameters	2007	2008	Pooled
OMY	16653	13033	14843
Sdo	2676	1695	1864
SMY	16119	13667	13667
SDs	2852	2038	2038
R	0.94**	0.68*	0.73*
Student 't'	0.09264 ^{NS}	0.17621 ^{NS}	0.01713 ^{NS}
MAE	850	1409	1363
MBE	-535	634	-1177
RMSE	1101	1586	1822
PE	6.6	12.2	12.3
Index of agreement (D)	0.99	0.97	0.98

As against this, the performance of the model in simulating GPSM was found to have been better in 2007 than in rest of the periods. All the test criteria were observed to be better for 2007 than those corresponding ones for 2008. The results, however, indicated the weakness of the model in simulating GPSM values. This result corroborated the finding of the

Jintrawat (1995) for evaluation the CERES-Rice for grain number per square meter with the range of 15 to 50% between simulated and observed ones.

4.3.4.5. Grain number per panicle

The observed and simulated values for grain number per panicle and their mutual association are depicted in Fig. 4.21 a to c for 2007, 2008 and for pooled data, respectively. Similarly various test criteria for evaluation of the performance of the model are presented in Table 4.28.

Results showed good association between observed and simulated values in 2007 in comparison with those for the rest of the period. The model was observed to have overestimated the number of grains per panicle for 2008 and also for the pooled data on a few occasions as was clearly evident from the positive values of the mean bias error (Table 4.28).

Table 4.28: Test criteria in evaluation of model with respect to grain numbers per panicle

Parameters	2007	2008	Pooled
OMY	21.0	18.6	19.9
Sdo	2.4	3.1	2.1
SMY	21.0	19.2	20.1
SDs	2.7	2.7	2.3
R	0.90**	0.40	0.71*
Student 't'	0.17165 ^{NS}	0.95199 ^{NS}	0.57847 ^{NS}
MAE	1.2	2.1	1.2
MBE	0.05	0.58	0.31
RMSE	1.4	2.7	1.6
PE	7.7	12.8	8.2
Index of agreement (D)	0.99	0.90	0.96

Crop yield in the CERES models is determined as a product of the grain numbers per plant and the average grain weight at physiological maturity. The grain number is calculated from the above ground biomass

during a critical stage in the plant growth cycle for a fixed thermal time before anthesis. In this study, the model had underestimated the above ground biomass during 2007 and overestimated during 2008. This fact could have contributed to the overestimation of grains per panicle.

4.3.4.6. Test weight

The association between the observed and corresponding simulated test weight of various cultivars of rice during 2007, 2008 and for pooled data is depicted respectively in Fig. 4.22 a to c. Figures clearly indicated that the model underestimated the test weight except in case of a few events. The values of MBE which were -1.43, 0.10 and -0.81 for 2007, 2008 and for pooled data (Table 4.29), also supported this inferences. However, the performance of the model in simulating test weight in the year 2008 was relatively good with lowest RMSE (1.16), MBE (0.10) and MAE (0.97).

Table 4.29: Test criteria in evaluation of model with respect to test weight

Parameters	2007	2008	Pooled
OMY	21.23	20.18	20.78
Sdo	2.24	1.70	1.31
SMY	19.79	20.29	19.97
SDs	0.72	1.14	0.79
R	0.97**	0.98**	0.95**
Student 't'	0.05723 ^{NS}	0.77365 ^{NS}	0.029662 ^{NS}
MAE	1.93	0.97	1.06
MBE	-1.43	0.10	-0.81
RMSE	2.66	1.16	1.35
PE	12.54	5.69	6.50
Index of agreement (D)	0.98	0.99	0.95

Similar results have also been reported by Hundal and Kaur (1999) in their 1985-86 simulation study. More (2000) observed underestimation of sorghum kernel weight as simulated by CERES-Sorghum model for sorghum cv. CSH-9. The findings of Varshneya (1999) for sorghum cv.

Swati and M 35-1 were also in good conformity with the findings of this study.

4.3.4.7. Harvest index (HI)

The observed and simulated harvest index values during 2007, 2008 and for pooled are depicted in Fig. 4.23 a to c. Results showed that the values of simulated harvest index were found to have been underestimated when compared with corresponding observed values except at few points in 2007, 2008 and pooled basis. This underestimation was the consequences of the overestimation of above ground dry matter production as simulated by the model (Fig. 4.9 to 4.11). The various test criteria as presented in Table 4.30 showed that the overall performance of the CERES-Rice model in simulating the harvest index was found to be good.

Table 4.30: Test criteria in evaluation of model with respect to harvest index

Parameters	2007	2008	Pooled
OMY	0.260	0.244	0.252
Sdo	0.030	0.007	0.013
SMY	0.258	0.238	0.248
SDs	0.030	0.011	0.015
R	0.80**	0.81**	0.73**
Student 't'	0.71289 ^{NS}	0.00574 ^{NS}	0.19887 ^{NS}
MAE	0.014	0.004	0.008
MBE	-0.002	-0.006	-0.004
RMSE	0.018	0.009	0.011
PE	6.83	3.600	4.33
Index of agreement (D)	0.98	0.99	0.97

4.3.4.8. Sensitivity analysis of CERES-Rice model to various weather and non weather parameters

Tropical countries are more vulnerable to climatic effects in agricultural productivity. Simulation models provide a scientific approach to study the impact of climate change on agricultural production and world food security. Sensitivity test of the crop simulation model is the process by which various input parameters are evaluated with regards to their importance relative to simulation relations. Here, an effort has been made to test the model under two situations in terms of mathematical logic and stability to extreme values of weather and non-weather parameters. The weather parameters selected for this purpose were photoperiod (± 0.5 to ± 2.5 hours), maximum and minimum air temperature (± 1 to $\pm 5^{\circ}\text{C}$), solar radiation (± 1 to $\pm 5 \text{ MJm}^{-2} \text{ day}^{-1}$) and concentration of carbon dioxide (40 and 80 ppm higher concentration over 330 ppm), while the non-weather parameters included plant population (25 to 200 plants per m^2), transplant age of seedling (15 to 40 days old) and methods of planting (Direct sowing). The simulated yields under optimum conditions were considered as reference or base yield and the conditions established to generate these results as base conditions (Second date of transplanting). The potential condition was assumed with congenial weather and no limitation of water. The simulation was done for Nawagam environment, *khari*f 2007, since the potential yield recorded in that season was more than that recorded for *khari*f 2008. The present study was carried out mainly to establish the sensitivity of CERES-Rice model in relation to grain yield of various genotypes of aromatic rice affected by various weather and non weather parameters.

4.3.4.8.1. Effects of photoperiod

The examination of the data presented in the Table 4.31, on sensitivity of CERES-Rice simulated grain yield under altered weather parameters indicated that with incremental unit increase in day length,

the simulated yield increased linearly and *vice versa*. The percentage change over base yield was highest recorded in the case cv. Gr-104 and lowest in cv. Pankhali. However, percentage change from base yield was relatively high with decreased levels of photoperiod and rate of percentage change was negative after 2.0 hours increment in all the genotypes except Pusa Basmati-1 (Fig. 4.24). This result might be due to the increased crop duration from 8.8 (Pusa Basmati-1) to 11.9% (GR-104) change over base maturity days. Since, rice crop is a short day plant, any increase in photoperiod delay the flowering. Hence, longer vegetative phase resulted in to higher dry matter production converted in to higher grain yield.

4.3.4.8.2. Effects of solar radiation

The results of varying solar radiation and its effects on grain yield as simulated by CERES-Rice model for various genotypes of rice are presented in Table 4.32. Results showed that with increase from 1 to 5 MJm⁻² day⁻¹ solar radiation, percentage yield increased gradually in comparison with base yield in case of cv. Pankhali and GR-104. However genotype Narmada and Pusa Basmati-1 did not show such gradual increment in percentage change over base yield up to increment of 5 MJm⁻² day⁻¹ (Fig. 4.25). In case of gradual reduction in solar radiation, gradual decrease in yield in terms of per cent change from base yield was noted in all the four genotypes, but reduction was almost up to 50% was recorded in case of cv. GR-104. It was interested to know that reduction in yield due to gradual reduction in solar radiation per day was higher than that of percentage change in yield due to increment of it for same unit. Thus, a scrutiny of the overall response of varying radiation to grain yield of rice cultivars showed that the model was more sensitive to radiation than it was to photoperiod. This result was

in close association with the finding of Pathak *et al.* (2003) for rice and wheat crops.

4.3.4.8.3. Effects of maximum air temperature

The effects of altered maximum air temperature (± 1 to $\pm 5^{\circ}\text{C}$) on simulated grain yield of various cultivars of rice under optimal date of transplanting and the comparison of this simulated grain yield with base yield and its per cent change from base yield are presented in Table 4.33.

Sensitivity of CERES-Rice model simulated grain yield to incremental units of maximum air temperature showed a gradual decrease in yield while the down scaled maximum temperature increased the yield in all four genotypes of rice (Fig 4.26). Maximum reduction in yield due to increment of same unit of maximum temperature was recorded in GR-104 genotype where as cv. Pankhali recorded least reduction for corresponding temperature level. The highest positive percentage change in yield over base yield due to reduction of maximum temperature was recorded in Pusa Basmati-1 and least by the genotype GR-104. Such behavior of the model was mainly due to reduction in duration of anthesis and grain filling with rise in ambient temperature and *vice versa* (Aggarwal and Sinha, 1993; Aggarwal and Kalra, 1994b for wheat crop and Muchow *et al.*, 1997 for sugarcane). This result was in close association with the experimental finding of the zhiqing *et al.* (1995) for the rice crop. Pathak *et al.* (2003) also stated on the basis of sensitivity analysis of CERES-Wheat that elevated maximum temperature decreased wheat yield significantly. Similar results were reported by the Karim *et al.* (1994) and Escano and Buendia (1994) in sensitive analysis to the temperature and CO₂ concentration of the CERES-Rice model.

4.3.4.8.4. Effects of minimum air temperature

The result of simulated yield when examined in relation to minimum temperature indicated decrease in yields with increase in

temperature above that corresponding to potential conditions in all four genotypes of rice. But the magnitude of change from base yields in terms of percentage was almost double that corresponding to the preceeding level in all the increased level of maximum temperature in the case of Pankhali and Pusa Basmati-1 cultivars (Table 34). This type of behaviour shown by the crops might be due to dual effects of higher rate of respiration during night time resulted in to comparatively higher loss of photosynthates than that was occurred during day time due to increased maximum temperature and differential reduction in crop duration of different cultivars of rice. The reduction was however, less for the heat tolerant cultivar (Pankhali). This result highly corroborated the findings of Singh and Ritchi (1993) for the sensitive evaluation to the climate change of the CERES-Rice for heat sensitive (IR-58) and heat tolerant (imaginary) cultivars of rice. Paradoxically, the low minimum temperature increased the yield in the all four genotypes of rice, but not in the same magnitude as that of reduction in yield with increase in minimum temperature and decrease in maximum temperature (Fig. 4.27). All the four genotypes behaved differently in relation to change in minimum air temperature as the simulated yield did not increased linearly when minimum temperature was decreased up to 5°C in the case of Narmada and GR-104 genotypes. This result described the tolerant power of various genotypes of rice in relation to minimum temperature where, growth rate affected differently in different cultivars.

4.3.4.8.5. Effect of elevated carbon dioxide

Global warming and the green house effect, the present buzz words among the scientific community invoked interest to the behavior of the model to elevated level of CO₂. The effect of elevated carbon dioxide (40 and 80 ppm higher concentration over the base value 330 ppm) on simulated grain yield of various cultivars of rice under optimum

condition in relation to base yield have been depicted in Fig. 4.28. Elevated levels of CO₂ by 370 and 410 ppm increased grain yields as simulated by the model by 3.3 to 21.0, 3.7 to 23, 6.9 to 27.9 and 4.9 to 25.6 (Table 4.35) in cv. Pankhali, Narmada, GR-104 and Pusa Basmati-1 respectively when compared with base yield. Lal *et al.* (1998) observed that a 3°C rise in temperature (under elevated CO₂ concentration) nearly cancelled out positive effect of elevated CO₂ on the wheat and rice yields as studied through use of CERES-Wheat and rice models for North West India. This clearly showed that elevated concentration of CO₂ had a significant and positive impact on the grain yield of various genotypes of rice, but GR-104 could be performed better under elevated concentration of rice than that of other genotypes.

Similar results were found by Baker *et al.* (1990b), Singh and Padila (1995), Saseendran *et al.* (2000) for the case of rice crop using CERES-Rice model.

Table: 4.35. Sensitivity of CERES-Rice model to elevated CO₂ concentration for various cultivars of rice

Cultivars	Elevated CO ₂ concentration				
	Base yield (kg ha ⁻¹)	370 ppm		410 ppm	
		Simulated grain yield (kg ha ⁻¹)	% Change from base yield	Simulated grain yield (kg ha ⁻¹)	% Change from base yield
Pankhali	3793	3919	3.3	4589	21.0
Narmada	4243	4400	3.7	5241	23.5
Gr-104	4887	5225	6.9	6250	27.9
Pusa Basmati-1	4177	4382	4.9	5247	25.6

This study also revealed that doubling the CO₂ concentration caused an increase in yield by 40% due to higher assimilation rates as observed in case of results simulated by SUCROS87 model for wheat. Jamieson *et al.* (2000) tested the performance of the models AFRCWHEAT2, FASSET and Sirius by elevated CO₂ and showed that the

effects of elevated CO₂ on grain yields of wheat were expressed through the effects on light use efficiency (LUE). Matthews *et al.* (1997) found through the use of General Circulation Model in case of rice that under doubled CO₂ concentration the yield increased. Lal *et al.* (1998) and Hoogenboom *et al.* (1997) also worked on impact of climate change and found similar response on the grain yield of rice and wheat under elevated CO₂ concentration. This showed that the model used in this study had the potential for assessing the impacts of climate change on rice production. Properly validated crop simulation models could be used with confidence to combine the environmental effects on crop physiological processes and to evaluate the consequences of such influences.

4.3.4.8.6. Effects of planting methods

The change in planting method (Direct sowing) and their impacts on grain yields of various cultivars of rice as simulated by the model in comparison with base yield are presented in Fig. 4.29. The yield reductions ranged between 12.4 (GR-104) to 14.4 (Pusa Basmati-1) percentage change from base yield. This indicated that the model functioned extremely well in detecting the effect of planting methods on simulated yield of rice.

4.3.4.8.7. Effect of transplant age of seedling

The striking features observed while studying the sensitivity analysis of CERES-Rice model to transplant age of seedling was that the magnitude of percentage change ranged between -3.0 to -22.0 (Table 4.36) from base yield when transplant age was increased 5 to 15 days from optimum age (25 days old). However, the magnitude of percentage change from base yield was more or less same among the various cultivars of aromatic rice (Fig. 4.30). Hundal and Kaur (1999) reported similar result in evaluation of the age of seedlings for rice using CERES-

Rice model. There was no noticeable change in simulated yield was observed when sensitivity of CERES-Rice model was analysed with decreased transplant age of all four cultivars. Establishment of crops could be lower in the case of transplanting of the tender (less than 25 days old) seedlings as lack of proper growth of the roots.

4.3.4.8.8. Effect of plant population

The varying plant population per square meters and its impact on grain yield of various cultivars of rice in comparison with base yield are depicted in Fig. 4.31. Large yield reductions were observed on decreasing plant population up to 25 plants per sq. meter in all cultivars, but Pusa Basmati-1 recorded highest (Table 4.37). However, model did not show any noticeable percentage change when compared with the base yield in relation to increasing the plant population from 75 to 200 per sq. meter. This showed the insensitivity of the model to varying plant population level. Dhaliwal *et al.* (1997) revealed that with increase in plant population in wheat crop yields as simulated by CERES-Wheat model levels off after certain limits on the plant population.

CERES-Rice simulated grain yield increased linearly with increased day length as well as solar radiation and *vice versa* irrespective of cultivars. But model simulated grain yield decreased under increased scenario of maximum and minimum temperature, percentage change in simulated yield over base yield was higher in the case of minimum temperature than the maximum temperature for same unit of alteration. Model was found enough sensitive for quantifying the effect of the change in concentration of the CO₂ level on the grain yield of the various cultivars of rice. The simulated grain yield of rice was highly affected by methods of transplanting and transplant age of seedling. However, model showed more or less insensitiveness for change in plant population. This behaviour of the model indicated the need of modification of the plant population subroutine.

Summary and Conclusion

V. SUMMARY AND CONCLUSION

5.1. General

This chapter describes brief and precise summary of the procedures and techniques followed, findings achieved and conclusions drawn through the study entitled “Simulation of environmental and varietal effects on growth and yield of aromatic rice using CERES-Rice model in middle Gujarat Agro-climatic region.” The study was carried out for purposes of simulation of phenology, growth and yield of four different cultivars of rice (cv. Pankhali, Narmada, GR-104 and Pusa Basmati-1), validation of three dates of transplanting, calibration of genetic coefficients of various rice cultivars and to carry out the sensitivity analysis of CERES-Rice model with respect to middle Gujarat agro-climatic region.

Rice production has been increased tremendously due to increase in area under rice as well as productivity; there is still tremendous scope for increasing the yield by improving efficiency of current agricultural systems through efficient management. In order to sustain higher production and minimize the environmental derogatory influences of varying and uncertain conditions, understanding of crop growth in relation to varying resource input and agro-environments for management options is required. The detailed quantification of growth response should have the capability of answering yield variations due to variations in weather, space, time, cultivar characteristics and soil environment. Improved production technology at the farm level is the most crucial starting point for improving the productivity of rice in future by employing and appropriately adapting suitable crop growth simulation models. In addition to this, the use of crop yield simulation models comes handy to the government agencies, trade and industry for planning distribution, storage, processing, and export/import of crop produce besides taking timely policy decisions on fixing levy prices as they provide a reliably accurate advance estimation of yields. Crop simulation models are recent tools

that can facilitate identification of production constraints and assist in agro-technology transfer. They are widely used as a management tool to evaluate the effects of climate, soil, hydrologic and agronomic factors on crop yield and its variability. It is not unlikely that use of crop simulation model will definitely improve agronomic weather information and interpretation in time to come and farmers will be able to reduce production risks and increase crop yield by tailoring management decisions to current and expected weather.

In the present investigation the Crop Environment Resource Synthesis (CERES) Rice model which is described by Ritchie and Otter (1985), Ritchie (1986) and Godwin *et al.* (1990) and which forms the basis of IBSNAT: International Benchmark Sites Network for Agro-technology Transfer (Uehara, 1985) was used to calibrate pertinent genetic coefficients and to validate it for various cultivars of rice in middle Gujarat Agro-climatic region.

5.1.1. Objectives and methodology

The study was carried out with the broad objectives of simulating phenology, growth and yield of four cultivars of rice (cv. Pankhali, Narmada, GR-104 and Pusa Basmati-1) after calibrating the required genetic coefficients for Nawagam (Gujarat) condition under different microenvironment.

5.1.2. Calibration and validation of CERES-Rice model

The CERES-Rice model was calibrated and validated with the data sets generated during *kharif* seasons of 2007 through field experiment with four cultivars and three dates of transplanting on Silty Loam soils of the Reasearch Farm of Main Rice Research Station, Nawagam, Anand Agricultural University, Anand.

The various agronomic observations coinciding with critical growth stages of crop as recorded during the study were; days to anthesis and maturity, leaf area, total above ground dry matter and other biometric observations such as, number of leaves, number of grains per sq. meter, number of grains per panicles etc. The final grain and straw yields of

individual year and also from the relevant data subjected to pooled over the seasons to ascertain the best treatment and high yielding cultivars. The crop genetic coefficients were derived iteratively using Hunt's method (Hunt *et al.*, 1993). For purposes of determination of genetic coefficients, the model was run several times using a range of values of each coefficient in the sequential order of the plant growth events and parameters viz., date of emergence, anthesis, maturity, grain yield, biomass, grain density and weight until the desired level of agreement between simulated and observed values of crop growth, development and phenology was reached. Comparisons were made between the model simulated and observed growth and yield parameters.

Validation of the model was done using different test criteria (summary, difference and descriptive measures). Mean absolute error (MAE), mean bias error (MBE) and root mean square error (RMSE), PE were the difference measures, which located and quantified the errors. Index of agreement (D) was also employed to judge the model performance. In addition to these, error percent, correlation coefficient and 't' test were also carried out to express the deviation in simulated values from those observed.

5.1.3. Sensitivity analysis of the CERES-Rice model

The results of the sensitivity analysis of the model were studied for optimum dates of transplanting for all four genotypes of aromatic rice with respect to the weather data of the years 2007. The weather parameters selected for this purpose were photoperiod, solar radiation and ambient (maximum and minimum) temperature with their respective incremental units ranging between ± 0.5 to ± 2.5 (h), ± 1 to ± 5 MJ m⁻² day⁻¹, and ± 1 to $\pm 5^\circ\text{C}$. In addition to these, two elevated levels of carbon dioxide (370 and 410 ppm) were also included in the studies. Under non-weather parameters planting method (direct sowing), plant population (25 to 200 m⁻²) and transplant age of seedlings (15 to 40 days) were evaluated for their role and influences on yield.

5.2. Summary of the results

5.2.1. Grain yield

The genotype GR-104 yielded the highest irrespective of dates of transplanting among various cultivars of aromatic rice taken in the experiment during both crop years as well as on pooled data basis. It was due to higher accumulation of photosynthates in to biomass from higher leaf area index in genotype GR-104 than that of others cultivars. The treatment D₂ (22nd July) transplanting gave the highest yield in all the cultivars as compared to the yields realized from the treatments D₁ and D₃. The comparison of the results of grain yield during 2007 and 2008 separately as well as pooled basis revealed that differences in yield due to differences in the microenvironment created due to different dates of transplanting.

Consistency in the best performance of the second date of transplanting was observed in all the four different cultivars of aromatic rice and this was mainly attributed to more congenial weather that prevailed during this period as compared the weather that prevailed during the D₁ and D₃ transplanting. The prevalence of the lowest average maximum temperature in D₂ (31.4°C) during flowering (around 100 DAS) phase in 2007 crop growing season and 30.5 to 31.0°C during same growth phase (around 80 to 90 DAS, as early flowering was observed) during 2008 for same transplanting helped in maximizing the grain yield. The average minimum temperature in the second date of transplanting during both the years was the lowest (17.5 and 23.5°C in 2007 and 2008) in comparison with that which correspondingly prevailed in the treatments D₁ and D₃. The lowest value of the average maximum temperature throughout the growing season and relatively low values of average minimum temperature during panicle initiation to beginning of grain filling in treatment D₂ proved themselves congenial for higher grain yield. The average mean temperature i.e., 25.9 and 27.4°C in 2007 and 2008 respectively was also lower in D₂ in comparison to other date of transplanting during both

the crop season. Considerably lower mean temperatures prevailed during the flowering and milking stages of the crop grown under D₂ and their beneficial effect was reflected in the grain yield during both the crop year.

The association of simulated grain yield in case of cv. GR-104 was found in perfect agreement with the correspondingly measured ones. While, the association between simulated and observed grain yields of Pankhali, Narmada and Pusa Basmati-1 cultivars were found satisfactory, when pooled over the years. However, over/under estimation of yield was also recorded in individual years for respective cultivars and this pointed out a scope for further improvement of the model. The error percentage in pooled data ranged between 0.5 (V₄D₃) to 12.1 (V₁D₁). Simulation performance of the model was in perfect agreement under all treatments except in V₁D₁ treatment. Various test criteria used for ascertaining the performance of the model suggested that the simulated grain yield was positive and significantly associated with observed ones during both crop seasons as well as when pooled over the years. However, the evaluation of the model on an overall basis revealed that the simulation performance of the model in respect of grain yield was perfect on pooled basis than in any other period.

5.2.2. Above ground biomass

The overall trend of the above ground biomass productions of four different genotypes of aromatic rice under different dates of transplanting was similar to that of grain yields. The second date of transplanting (D₂) recorded highest above ground biomass production irrespective of cultivars during both the crop years and pooled basis. This treatment was followed by treatments D₃ and D₁ in succession in respect of above ground biomass in the case of Pankhali and Narmada where as in the case of GR-104 and Pusa Basmati-1, D₂ was followed by D₁ and D₃. However, the difference between treatments D₁ and D₃ were found to be negligible with each other in this respect. This result might be due to higher average bright sunshine hours

encountered by the crop in D₂ transplanting than that of D₁ in crop season 2007 and D₁ and D₃ in 2008 along with other congenial weather conditions which favoured higher grain yield and straw yield. The above ground biomass production in D₃ during 2007 might be off set by the lower crop duration. The prevalence of low average minimum temperature in the second date of transplanting during both the years was the lowest (17.5 and 23.5°C in 2007 and 2008) in comparison with that which correspondingly prevailed in the treatments D₁ and D₃ were also found very much congenial for yielding the highest above ground biomass production.

The overall trend of simulated above ground biomass production indicated overestimation by the model except for few treatments. However, positive significant association was observed between simulated and observed biomass production during 2007, 2008 and for pooled data.

5.2.3. Phenological events

Perfect agreement between observed and simulated days to anthesis was recorded in D₂ transplanting for all genotypes except Narmada during crop season 2007. Where as overall results showed that days to anthesis decreased treatmentwise irrespective of cultivars from first to third date of transplanting, both in case of observed and simulated values. This decreasing trend could be explained in terms of the rate of development (inverse of duration) as related to temperature and photoperiod. The prolonged period of favourable temperature and lower photoperiod in addition to higher mean vapour pressure resulted in relatively more duration of days to anthesis under D₁ transplanting followed by D₂ and D₃.

The results of various test criteria revealed that the model underestimated the days to anthesis in crop season 2007 irrespective of cultivars where as, it was overestimated during 2008 and pooled basis by the model. However, the model performance in terms of simulation of days to anthesis was more satisfactory in 2007 than in 2008 and in pooled data. The

results also showed that more or less genotype GR-104 recorded highest mean error percent between simulated and observed days to anthesis among four different cultivars of aromatic rice where as, cv. Narmada recorded the least mean error percent.

In the matter of simulating the days to maturity, during first crop growing season the model simulated days to maturity underestimated the actual ones in the range between -2.0 to -5.0 d except in V₁D₁, V₁D₂ and V₄D₃. Where as, the model over estimated the days to maturity in all the treatments except V₄D₁ and V₄D₃ and the over estimation ranged from 1 to 11 d during crop season 2008. This overestimation was found to have an increasing trend from D₁ to D₃ transplanting in all genotypes. The range of magnitude of deviation between simulated and observed days to maturity varied between 0.0 to 4.0 d in various treatments on pooled data on days to maturity of crop season 2007 and 2008. Lowest values of mean deviation as recorded were 0.3 (V₁), 0.7 (V₄) and 0.8 d (V₃) during 2007, 2008 and the pooled data respectively. The highest magnitude of error per cent of deviation between simulated and observed days to maturity was recorded as 3.2% in V₃D₃ where as, perfect agreements between simulated and observed days to maturity were recorded by the treatments V₂D₁, V₃D₁ and V₃D₂. Model performance in terms of simulated days to maturity was found superior in 2007 to that in 2008 and also in case of pooled data.

5.2.4. Leaf area index

The measured as well as model simulated LAI was found maximum at the anthesis stage during both the years. Slightly low peak in LAI both in simulated and observed values was noticed at BGF (Beginning grain filling) due to additive effect of senescence of lower leaves started and vegetative growth had ceased at that stage. The values of LAI for various genotypes of rice were highest in D₂ transplanting and lowest in D₃ under measured as well as simulated conditions during both the years.

The highest LAI was recorded in GR-104 in all the corresponding dates of transplanting than that of others. The plants with high LAI intercepted maximum solar radiation, which was vital for photosynthetic activity of the leaves. In cereals, under most circumstances, majority of the carbohydrates in the grain are derived from carbon dioxide fixation (photosynthesis) after flowering stage. This was the reason for higher grain yield in respect of D₂ transplanting among various dates of transplanting irrespective of cultivars and also in GR-104 among different genotypes of rice. The simulated LAI values vary much from one another under different dates of transplanting as well as from genotype to genotype. This differential behaviour of the model showed that the function of LAI simulation in the CERES-Rice model needed to be modified for the improvement of the performance of CERES-Rice model.

5.2.5. Number of grains per square meter, grain number per panicle, test weight and harvest index

Simulated grains per sq. meter (GPSM) values were found to have been underestimated by the model when compared with the corresponding observed ones in most of the cases except under a few ones during 2007 and pooled data basis, where as model overestimated the GPSM during 2008 except in three treatments. Paired-'t' test between simulated and observed values showed that the differences were non-significant, but the correlation coefficient between observed and simulated values found significant both in 2007 and 2008 as well as pooled basis. The performance of the model in simulating GPSM was found to have been better in 2007 than in rest of the periods. All the test criteria were observed to be better for 2007 than those corresponding ones for 2008. The results, however, indicated the weakness of the model in simulating GPSM values. The results suggested that performance of the model in simulating GPMS for the crop-growing season of 2008 was poor. This result appeared to have been caused by poor estimation of above-ground biomass because grain numbers are calculated from above ground

biomass during a critical stage in the plant growth cycle for a fixed thermal time before anthesis.

The observed and simulated values for grain number per panicle and their mutual association was good in 2007 in comparison with those for the rest of the period. The model was observed to have overestimated the number of grains per panicle for 2008 and also for the pooled data on a few occasions as was clearly evident from the positive values of the mean bias error. The model underestimated the test weight except in case of a few events. The values of MBE which were -1.43, 0.10 and -0.81 for 2007, 2008 and for pooled data also supported this inferences. However, the performance of the model in simulating test weight in the year 2008 was relatively good with lowest RMSE, MBE and MAE. The various test criteria showed that the overall performance of the CERES-Rice model in simulating the harvest index was found to be good.

5.2.6. Sensitivity analysis

CERES-Rice simulated grain yield under altered photoperiod indicated that the simulated yield increased linearly with incremental unit increase in day length and *vice versa*. The percentage change over base yield was highest recorded in the case of GR-104 and lowest in Pankhali genotype. However, percentage of change from base yield was relatively high with decreased levels of photoperiod and rate of percentage change was negative after 2.0 hours increment in all the genotypes except Pusa Basmati-1. Since, rice crop is an essentially short day plant, any increase in photoperiod delay the flowering. Hence, longer vegetative phase resulted in to higher dry matter production converted in to higher grain yield.

Simulated grain yields were increased gradually in comparison with base yield with increase in solar radiation from 1 to 5 MJ m⁻² day⁻¹ in case of Pankhali and GR-104. However genotype Narmada and Pusa Basmati-1 did not show such gradual increment up to increment of 5 MJ m⁻² day⁻¹. In case

of gradual reduction in solar radiation, gradual decrease in yield in terms of per cent change from base yield was noted in all the four genotypes, but reduction was almost up to 50% was recorded in case of GR-104 cultivar. It was interested to know that reduction in yield due to gradual reduction in solar radiation per day was higher than that of percentage change in yield due to increment of it for same unit. Thus, a scrutiny of the overall response of varying radiation to grain yield of rice cultivars showed that the model was more sensitive to radiation than it was to photoperiod.

Sensitivity of CERES-Rice model simulated grain yield to incremental units of maximum air temperature showed a gradual decrease in yield while the down scaled maximum temperature increased the yield in all four genotypes of rice. Maximum reduction in yield due to increment of same unit of maximum temperature was recorded in GR-104 genotype where as Pankhali recorded least reduction for corresponding temperature level. The highest percentage change in yield over base yield due to reduction of maximum temperature was recorded in Pusa Basmati-1 and least by the Genotype GR-104. Such behavior of the model was mainly due to reduction in duration of anthesis and grain filling with rise in ambient temperature and vice versa.

Elevated levels of CO₂ by 370 and 410 ppm increased grain yields as simulated by the model by 3.3 to 27.9% in various cultivars of rice when compared with base yield. Genotype GR-104 recorded highest positive percentage change over base yield. Hence, GR-104 could be performed well under elevated concentration of rice than that of other genotypes. Simulated grain yield was decreased in comparison with base yield when direct sowing method was applied in all the four genotypes of rice. Large yield reductions were observed on decreasing plant population up to 25 plants per sq. meter in all cultivars, but Pusa Basmati-1 recorded highest. However, model did not show any noticeable percentage change when compared with the base yield in

relation to increasing the plant population from 75 to 200 per sq. meter. This showed the insensitivity of the model to varying plant population level.

The striking features observed while studying the sensitivity analysis of CERES-Rice model to transplant age of seedling was that the magnitude of percentage change ranged between -3.0 to -22.0 in various genotypes from base yield when transplant age was increased 5 to 15 days from optimum age (25 days old). There was no noticeable change in simulated yield was observed when sensitivity of CERES-Rice model was analysed with decreased transplant age of all four cultivars.

5.3. Conclusions

The following broad conclusions could be drawn from the results of the present investigation.

- (1) The GR-104 genotype of rice was found to be highest yielder among various cultivars of aromatic rice under middle Gujarat Agro-climatic region.
- (2) Second date (D₂-22nd July) of transplanting of the rice was found to be optimum for higher grain yield in all the four cultivars of aromatic rice under middle Gujarat Agro-climatic region.
- (3) The CERES-Rice model underestimated dry matter production and leaf area index. This result suggested that functional form of leaf area index simulation sub-routine needed to be revised as it has had a direct relevance with biomass production.
- (4) Grain yield of various cultivars of rice, days to anthesis, days to maturity, number of grains per square meter, grains number per panicle, test weight and harvest index were satisfactorily simulated by the CERES-Rice model under varying environmental condition. This clearly showed the robustness of the CERES-Rice model.
- (5) CERES-Rice model functioned extremely well in detecting the effects of variations in photoperiod, solar radiation, maximum and minimum air

temperature, concentration of carbon dioxide, plant population and planting methods and in simulating their impacts on grain yield of various cultivars of rice under varying environmental conditions.

- (6) The Pankhali genotype of rice could be suitable cultivar among four different cultivars taken in present investigation, in increased scenario of ambient temperature.
- (7) The CERES-Rice could be used to find alternative ways to improve rice production.

5.4. Future line of work

As CERES-Rice model overestimated biomass and leaf area, the functional forms of these two parameters in the model required revision and modification through recalibration.

The crop growth simulation models required to be calibrated at original code level for Indian farming conditions.

The DSSAT sequence model also needs to be further evaluated against observations for a range of locations and management using data from long-term experiments in Rice-Wheat systems.

The performance of the CERES-Rice model needs to be linked with GIS framework and assessment of crop condition and yield estimation through remote sensing for a more accurate forecast of the yield taking in to account the spatial and temporal variability in rice yield.

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Appendix

Appendix - I

Variation in weather elements during the crop season, *kharif* 2007

Date	Max Temp (°C)	Min Temp (°C)	BSS hrs	RF mm	WS kmph	RH Mor %	RH A/N %	Avg.VP mm of Hg
6/12/07	33.8	26.0	10.5	0.0	10.6	87.5	69.1	23.4
6/13/07	34.4	26.3	10.2	0.0	8.4	92.2	53.5	23.5
6/14/07	35.9	26.4	10.8	0.0	9.3	83.3	49.9	24.7
6/15/07	36.4	26.8	9.1	0.0	10.4	79.9	70.2	24.8
6/16/07	32.5	25.5	5.1	1.2	11.4	84.7	93.6	24.8
6/17/07	32.2	25.5	4.8	16.8	9.0	89.2	50.2	24.8
24 week	34.2	26.1	8.4	18.0	9.9	86.2	64.4	24.3
6/18/07	34.2	26.2	8.2	0.0	12.2	84.7	44.5	23.6
6/19/07	34.8	26.8	9.1	0.0	12.5	80.6	50.8	23.9
6/20/07	36.2	26.0	6.7	0.0	13.0	76.7	48.0	24.5
6/21/07	36.5	26.7	5.4	0.0	13.0	75.2	42.8	24.7
6/22/07	36.4	27.5	7.4	0.0	13.1	75.2	40.8	26.5
6/23/07	35.8	26.0	8.8	0.0	10.7	75.2	39.5	24.7
6/24/07	36.5	27.2	5.6	0.0	4.1	82.2	45.1	22.6
25 week	35.8	26.6	7.3	0.0	11.2	78.6	44.5	24.4
6/25/07	37.5	26.2	1.0	0.0	18.9	81.8	38.2	24.9
6/26/07	37.5	27.2	1.5	0.0	11.6	76.6	38.1	24.6
6/27/07	37.4	28.2	8.5	0.0	10.9	76.8	40.3	25.2
6/28/07	37.2	26.5	5.6	0.0	8.8	80.6	45.9	25.2
6/29/07	36.4	27.0	5.1	8.2	9.0	75.2	47.6	26.0
6/30/07	36.2	26.5	7.2	0.0	7.9	81.9	48.9	27.3
7/01/07	35.4	26.5	3.2	0.0	1.5	82.0	50.1	25.1
26 week	36.8	26.9	4.6	8.2	9.8	79.3	44.2	25.5
7/2/07	35.9	27.0	0.7	0.0	8.3	82.0	45.1	25.1
7/3/07	37.4	25.2	0.1	11.6	5.3	90.5	92.2	22.9
7/4/07	29.7	24.2	0.0	9.4	2.9	85.9	77.5	26.0
7/5/07	31.6	24.6	0.0	5.8	5.6	85.9	65.4	24.3
7/6/07	32.5	26.0	0.0	0.0	8.1	90.5	59.1	26.3
7/7/07	33.5	25.4	0.0	0.0	8.7	90.5	58.0	25.4
7/8/07	33.4	25.7	0.1	0.0	10.3	87.5	59.7	24.4
27 week	33.4	25.4	0.1	26.8	7.0	87.5	65.3	24.9
7/09/07	32.7	25.9	0.2	0.0	11.3	86.0	57.1	24.3
7/10/07	33.7	26.2	0.0	0.0	10.2	87.4	80.5	23.9
7/11/07	30.4	25.7	0.0	0.4	4.3	85.9	89.0	25.7
7/12/07	30.1	25.9	7.5	2.4	5.4	90.5	74.4	26.0
7/13/07	30.8	25.0	7.6	1.6	6.7	96.7	95.1	23.4
7/14/07	26.8	25.3	3.3	19.8	6.1	96.7	89.2	25.3
7/15/07	29.3	25.2	5.9	24.2	5.9	93.5	70.9	25.6
28 week	30.5	25.6	3.5	48.4	7.1	91.0	79.5	24.9
7/16/07	31.2	25.2	5.2	0.0	7.2	90.5	67.9	25.8
7/17/07	33.7	25.4	6.4	0.0	8.5	90.5	64.5	24.5
7/18/07	33.1	25.0	4.8	0.0	7.5	88.9	65.4	22.4
7/19/07	32.7	24.6	7.8	0.0	5.9	87.4	56.9	24.3
7/20/07	33.4	25.1	5.8	0.0	10.9	81.7	61.1	23.4
7/21/07	33.4	25.7	6.6	0.0	8.4	87.4	64.2	23.3
7/22/07	32.4	26.0	7.5	0.0	7.0	89.0	61.9	23.5
29 week	32.8	25.3	6.3	0.0	7.9	87.9	63.1	23.9
7/23/07	32.4	25.5	9.4	0.0	7.3	87.5	60.3	23.2
7/24/07	33.4	26.1	8.9	0.0	7.5	86.0	55.8	25.6
7/25/07	33.7	26.5	9.8	0.0	6.9	84.5	53.8	25.2
7/26/07	33.7	26.0	8.0	0.0	9.0	90.5	63.6	23.7
7/27/07	34.1	24.1	3.5	0.0	5.8	87.3	56.4	25.5
7/28/07	34.2	25.7	8.2	0.0	5.8	81.5	61.3	25.6
7/29/07	34.4	26.0	0.0	0.0	4.2	83.3	66.1	23.5
30 week	33.7	25.7	6.8	0.0	6.6	85.8	59.6	24.6

Date	Max Temp (oC)	Min Temp (oC)	BSS hrs	RF mm	WS kmph	RH Mor %	RH A/N %	Avg. VP mm of Hg
7/30/07	31.7	24.0	0.0	42.0	3.3	98.5	96.5	26.2
7/31/07	27.0	24.8	2.4	94.2	7.3	95.2	78.3	26.7
8/1/07	30.3	25.7	2.5	0.0	8.5	93.5	75.0	25.8
8/2/07	31.6	25.0	2.6	0.0	5.7	75.0	72.4	26.2
8/3/07	31.6	25.7	4.5	0.0	7.0	93.6	72.7	26.2
8/4/07	32.2	25.2	1.0	11.2	2.8	95.1	92.1	26.1
8/5/07	27.4	24.7	1.0	2.0	10.2	91.9	77.2	25.3
31 week	30.3	25.0	2.0	149.4	6.4	91.8	80.6	26.1
8/6/07	30.7	24.9	3.3	22.0	5.0	93.5	82.4	25.2
8/7/07	30.8	25.3	0.4	14.6	7.0	95.1	85.0	25.6
8/8/07	31.2	25.5	0.0	0.0	6.9	91.1	82.2	22.5
8/9/07	29.4	25.0	0.0	1.2	8.3	91.9	69.3	25.8
8/10/07	31.4	24.8	3.2	2.6	10.3	93.5	82.3	23.4
8/11/07	30.7	25.0	5.0	0.0	9.3	93.5	87.6	23.4
8/12/07	28.2	25.0	1.0	1.8	3.5	93.6	74.3	23.6
32 week	30.3	25.1	1.8	42.2	7.2	93.2	80.5	24.2
8/13/07	30.5	26.0	0.2	0.0	10.4	90.4	93.6	25.0
8/14/07	27.4	25.4	3.3	47.2	8.3	100.0	100.0	24.3
8/15/07	26.2	24.5	0.6	41.8	7.2	98.3	77.8	23.8
8/16/07	27.2	24.5	4.3	8.1	15.0	98.3	98.3	24.3
8/17/07	26.0	24.6	7.4	2.6	5.5	96.7	89.2	23.7
8/18/07	28.5	25.3	7.1	0.1	5.1	93.5	71.8	22.8
8/19/07	30.4	24.8	1.0	0.0	5.7	90.2	70.7	23.8
33 week	28.0	25.0	3.4	99.8	8.2	95.3	85.9	24.0
8/20/07	30.9	24.3	9.2	0.0	5.8	93.4	77.2	24.2
8/21/07	30.7	24.5	8.7	0.0	5.7	93.6	68.1	21.9
8/22/07	30.9	24.6	0.0	0.0	6.1	90.1	66.6	22.4
8/23/07	30.8	24.5	8.8	0.0	4.9	88.6	89.0	23.4
8/24/07	30.4	24.0	8.9	6.2	5.6	95.0	63.5	25.3
8/25/07	31.6	24.2	9.0	0.0	3.1	90.2	56.4	23.4
8/26/07	31.8	24.7	9.7	0.0	3.3	88.7	58.7	25.9
34 week	31.0	24.4	7.8	6.2	4.9	91.4	68.5	23.8
8/27/07	32.7	25.2	7.5	0.0	4.2	85.7	89.1	26.0
8/28/07	32.8	26.0	4.4	0.0	4.5	72.3	69.8	24.9
8/29/07	27.8	24.5	6.6	5.1	4.7	95.0	68.5	24.5
8/30/07	29.5	25.0	1.8	1.8	3.0	97.3	66.1	25.5
8/31/07	31.4	25.0	2.8	0.0	4.9	90.3	59.5	25.4
9/1/07	31.6	24.5	3.4	0.0	5.9	82.5	63.3	26.0
9/2/07	32.4	24.6	5.7	0.0	4.9	91.9	52.3	24.7
35 week	31.2	25.0	4.6	6.9	4.6	87.9	67.0	25.3
9/3/07	32.8	25.0	4.8	0.0	2.5	98.3	56.1	7.6
9/4/07	34.4	26.4	3.6	0.0	1.8	89.2	60.4	8.5
9/5/07	35.5	25.7	5.8	0.0	2.6	92.1	59.3	8.2
9/6/07	35.5	26.5	6.4	0.0	2.7	90.7	64.2	7.5
9/7/07	34.5	25.5	3.1	0.0	3.8	89.0	65.9	7.4
9/8/07	33.2	25.2	7.0	0.0	4.2	84.4	62.4	7.9
9/9/07	33.2	25.7	8.8	0.0	4.0	87.4	63.2	9.5
36 week	34.2	25.7	5.6	0.0	3.1	90.1	61.7	8.1
9/10/07	32.7	25.2	7.5	0.0	2.8	90.5	61.0	24.3
9/11/07	34.5	25.5	7.4	0.0	2.8	87.4	62.6	25.5
9/12/07	35.3	26.2	6.6	0.0	3.0	92.1	59.9	24.6
9/13/07	34.4	25.5	6.8	0.0	3.8	90.5	62.4	24.7
9/14/07	33.2	25.4	9.8	0.0	5.6	90.5	60.6	23.3
9/15/07	35.5	26.5	9.3	8.4	3.7	89.0	66.2	23.5
9/16/07	34.4	23.0	9.1	10.2	4.7	96.7	77.5	23.4
37 week	34.3	25.3	8.1	18.6	3.8	91.0	64.3	24.2
9/17/07	31.5	23.0	8.4	6.4	2.0	93.5	92.1	26.4
9/18/07	31.0	24.3	9.5	4.6	4.1	91.8	98.3	23.0
9/19/07	27.5	24.8	8.5	35.4	4.9	90.3	86.3	26.5
9/20/07	27.5	23.5	4.3	117.6	10.0	93.3	95.1	25.4
9/21/07	27.5	24.5	8.8	6.3	6.2	90.3	75.2	25.5

Date	Max Temp (°C)	Min Temp (°C)	BSS hrs	RF mm	WS kmph	RH Mor %	RH A/N %	Avg. VP mm of Hg
9/22/07	32.1	25.0	9.5	5.6	5.3	93.5	77.5	25.5
9/23/07	32.1	25.3	8.7	0.0	4.2	89.0	67.2	23.8
38 week	29.9	24.3	8.2	175.9	5.2	91.7	84.5	25.2
9/24/07	31.5	24.8	6.4	0.0	2.9	77.0	66.5	25.3
9/25/07	30.4	24.5	0.0	0.0	3.2	95.1	69.8	23.1
9/26/07	32.0	24.1	0.0	0.0	2.5	93.5	64.9	24.0
9/27/07	31.8	23.5	0.2	0.0	2.6	86.9	64.8	24.6
9/28/07	31.2	23.3	7.4	0.0	3.7	95.0	63.5	26.1
9/29/07	31.2	23.0	9.6	0.0	4.7	91.7	66.6	22.8
9/30/07	30.5	22.5	9.9	0.0	4.2	87.8	65.5	23.3
39 week	31.2	23.7	4.8	0.0	3.4	89.6	65.9	24.2
10/1/07	31.2	23.0	9.7	0.0	3.5	93.3	62.2	22.5
10/2/07	31.2	23.0	7.7	0.0	3.0	95.0	61.1	21.7
10/3/07	31.6	23.5	9.4	0.0	2.1	91.7	69.0	19.0
10/4/07	32.4	24.1	9.9	0.0	1.6	95.1	71.0	23.8
10/5/07	31.4	25.4	9.8	0.0	2.1	90.3	67.7	18.1
10/6/07	34.2	24.8	9.3	0.0	2.7	95.1	63.7	17.8
10/7/07	35.4	25.0	9.5	0.0	1.4	95.1	62.1	16.4
40 week	32.5	24.1	9.3	0.0	2.3	93.7	65.3	19.9
10/8/07	34.5	24.5	9.5	0.0	4.1	91.9	61.4	24.2
10/9/07	33.5	24.8	9.5	0.0	2.1	90.3	62.4	22.8
10/10/07	33.2	23.5	8.9	0.0	1.5	88.7	59.0	22.1
10/11/07	33.5	23.5	9.3	0.0	2.7	91.9	59.1	22.0
10/12/07	33.5	23.6	9.6	0.0	1.8	88.7	53.1	19.6
10/13/07	35.7	23.4	10.3	0.0	1.9	87.4	48.8	23.0
10/14/07	38.5	23.1	9.9	0.0	1.3	92.0	49.9	17.9
41 week	34.6	23.8	9.6	0.0	2.2	90.1	56.3	21.7
10/15/07	36.6	21.5	10.2	0.0	1.1	84.1	37.9	15.9
10/16/07	37.5	20.7	10.2	0.0	1.0	74.6	37.5	26.2
10/17/07	36.3	20.1	9.8	0.0	1.3	82.1	90.1	38.2
10/18/07	35.5	21.2	9.8	0.0	2.2	88.0	47.7	25.6
10/19/07	35.1	21.6	9.1	0.0	3.0	57.8	50.2	14.7
10/20/07	34.4	21.5	9.8	0.0	2.4	76.9	44.9	14.1
10/21/07	35.2	19.4	9.7	0.0	2.8	76.5	36.7	14.3
42 week	35.8	20.9	9.8	0.0	2.0	77.1	49.3	21.3
10/22/07	35.7	18.2	9.8	0.0	1.5	72.7	30.2	15.3
10/23/07	35.5	17.9	9.1	0.0	2.0	80.8	37.4	14.2
10/24/07	34.8	18.2	8.3	0.0	1.7	68.6	32.8	15.8
10/25/07	35.5	17.6	7.3	0.0	1.8	71.0	31.3	13.5
10/26/07	35.7	18.0	9.3	0.0	1.5	74.8	35.1	12.7
10/27/07	35.8	17.5	9.3	0.0	1.7	79.1	24.0	14.0
10/28/07	35.7	18.2	9.3	0.0	1.7	72.6	26.2	14.6
43 week	35.5	17.9	8.9	0.0	1.7	74.2	31.0	14.3
10/29/07	35.0	17.9	9.3	0.0	2.4	74.6	29.3	13.3
10/30/07	36.2	17.1	8.8	0.0	2.8	84.5	32.5	12.0
10/31/07	34.2	17.2	9.1	0.0	2.8	86.2	33.4	13.9
11/1/07	34.2	17.4	9.3	0.0	3.1	84.5	32.7	15.4
11/2/07	33.6	18.0	9.3	0.0	2.2	74.8	32.9	15.0
11/3/07	33.8	16.8	8.7	0.0	1.5	80.4	27.9	15.3
11/4/07	35.5	16.5	8.8	0.0	1.3	83.8	26.3	16.6
44 week	34.6	17.3	9.0	0.0	2.3	81.3	30.7	14.5
11/5/07	34.8	17.5	7.1	0.0	2.7	78.5	22.9	22.7
11/6/07	35.4	17.0	9.2	0.0	1.3	86.3	25.4	13.5
11/7/07	35.3	17.9	9.5	0.0	3.1	80.3	31.6	14.4
11/8/07	34.3	17.3	9.4	0.0	2.9	90.9	32.5	15.3
11/9/07	34.4	16.0	8.6	0.0	2.4	67.5	28.1	16.4
11/10/07	34.3	16.5	8.8	0.0	3.0	63.5	28.6	13.9
45 week	34.6	16.0	9.2	0.0	0.9	86.6	30.0	14.0
11/5/07	35.4	15.8	8.8	0.0	2.1	57.1	29.4	13.0
11/6/07	33.2	15.5	8.9	0.0	2.8	53.3	18.9	11.6
11/7/07	33.2	14.0	8.8	0.0	2.8	80.5	26.1	10.7

Date	Max Temp (°C)	Min Temp (°C)	BSS hrs	RF mm	WS kmph	RH Mor %	RH A/N %	Avg. VP mm of Hg
11/8/07	33.5	14.4	8.8	0.0	1.1	88.1	27.7	11.4
11/9/07	32.6	13.4	8.5	0.0	1.1	80.6	25.8	11.5
11/10/07	33.4	13.5	8.4	0.0	1.3	76.1	28.1	10.6
11/11/07	32.2	14.0	8.3	0.0	2.1	84.2	34.8	7.9
46 week	33.4	14.4	8.6	0.0	1.9	74.3	27.2	10.9
11/19/07	32.5	17.2	8.4	0.0	2.9	61.7	27.2	7.3
11/20/07	31.8	22.1	8.3	0.0	8.1	56.5	54.8	7.6
11/21/07	29.6	20.7	8.9	0.0	7.8	58.5	55.2	11.3
11/22/07	31.5	17.5	8.9	0.0	2.9	71.1	25.3	8.6
11/23/07	31.9	14.0	9.1	0.0	6.3	42.0	30.4	7.7
11/24/07	30.5	16.5	8.5	0.0	8.6	55.0	35.5	10.0
11/25/07	30.5	15.5	9.2	0.0	7.5	46.8	34.4	9.3
47 week	31.2	17.6	8.8	0.0	6.3	55.9	37.5	8.8
11/26/07	30.8	14.3	9.3	0.0	5.9	55.0	30.6	10.2
11/27/07	32.5	12.1	8.7	0.0	2.3	64.0	28.5	9.4
11/28/07	33.4	14.4	8.7	0.0	2.0	62.3	27.4	11.0
11/29/07	32.7	14.8	7.4	0.0	4.3	60.8	24.4	12.0
11/30/07	31.7	16.7	5.0	0.0	6.3	53.7	24.4	11.8
12/1/07	30.0	16.5	7.1	0.0	8.4	49.8	36.5	13.5
12/2/07	30.5	21.2	8.0	0.0	7.2	42.4	45.2	13.3
48 week	31.7	15.7	7.7	0.0	5.2	55.4	31.0	11.6

Variation in weather elements during the crop season, *kharif* 2008

Date	Max Temp (°C)	Min Temp (°C)	BSS hrs	RF mm	WS kmph	RH Mor %	RH A/N %	Avg.VP mm of Hg
6/12/08	35.9	26.4	7.0	0.0	9.3	83.3	49.9	23.5
6/13/08	36.4	26.8	4.3	0.0	10.4	79.9	70.2	24.5
6/14/08	32.5	25.5	3.2	1.2	11.4	84.7	93.6	24.9
6/15/08	32.2	25.5	1.7	16.8	9.0	89.2	50.2	23.1
6/16/08	34.2	26.2	5.7	0.0	12.2	84.7	44.5	21.4
6/17/08	34.8	26.8	1.7	0.0	12.5	80.6	50.8	23.5
24 week	34.3	26.2	4.3	18.0	10.5	85.0	59.0	23.7
6/18/08	36.2	26.0	1.6	0.0	13.0	76.7	48.0	22.8
6/19/08	36.5	26.7	0.0	0.0	13.0	75.2	42.8	21.0
6/20/08	36.4	27.5	0.0	0.0	13.1	75.2	40.8	20.5
6/21/08	35.8	26.0	0.4	0.0	10.7	75.2	39.5	20.5
6/22/08	36.5	27.2	1.0	0.0	4.1	82.2	45.1	22.8
6/23/08	37.5	26.2	3.8	0.0	18.9	81.8	38.2	20.7
6/24/08	37.5	27.2	3.1	0.0	11.6	76.6	38.1	21.0
25 week	36.6	26.7	1.4	0.0	12.1	77.6	41.8	21.3
6/25/08	37.4	28.2	3.8	0.0	10.9	76.8	40.3	21.6
6/26/08	37.2	26.5	5.2	0.0	8.8	80.6	45.9	22.4
6/27/08	36.4	27.0	8.7	8.2	9.0	75.2	47.6	22.1
6/28/08	36.2	26.5	8.0	0.0	7.9	81.9	48.9	22.4
6/29/08	35.4	26.5	1.3	0.0	1.5	82.0	50.1	22.9
6/30/08	35.9	27.0	5.0	0.0	8.3	82.0	45.1	23.1
7/01/08	37.4	25.2	1.9	11.6	5.3	90.5	92.2	25.5
26 week	36.6	26.7	4.8	19.8	7.4	81.3	52.9	22.8
7/2/08	29.7	24.2	0.1	9.4	2.9	85.9	77.5	24.9
7/3/08	31.6	24.6	0.0	5.8	5.6	85.9	65.4	23.6
7/4/08	32.5	26.0	3.9	0.0	8.1	90.5	59.1	23.7
7/5/08	33.5	25.4	4.0	0.0	8.7	90.5	58.0	23.4
7/6/08	33.4	25.7	4.8	0.0	10.3	87.5	59.7	23.0
7/7/08	32.7	25.9	2.8	0.0	11.3	86.0	57.1	23.1
7/8/08	33.7	26.2	0.8	0.0	10.2	87.4	80.5	23.9
27 week	32.4	25.4	2.3	15.2	8.2	87.7	65.3	23.7
7/09/08	30.4	25.7	0.0	0.4	4.3	85.9	89.0	23.9
7/10/08	30.1	25.9	0.0	2.4	5.4	90.5	74.4	24.4
7/11/08	30.8	25.0	0.0	1.6	6.7	96.7	95.1	25.0
7/12/08	26.8	25.3	0.0	19.8	6.1	96.7	89.2	25.2
7/13/08	29.3	25.2	0.0	24.2	5.9	93.5	70.9	24.4
7/14/08	31.2	25.2	1.9	0.0	7.2	90.5	67.9	24.7
7/15/08	33.7	25.4	7.0	0.0	8.5	90.5	64.5	24.3
28 week	30.3	25.4	1.3	48.4	6.3	92.1	78.7	24.6
7/16/08	33.1	25.0	4.5	0.0	7.5	88.9	65.4	23.9
7/17/08	32.7	24.6	5.3	0.0	5.9	87.4	56.9	22.9
7/18/08	33.4	25.1	5.0	0.0	10.9	81.7	61.1	23.2
7/19/08	33.4	25.7	4.3	0.0	8.4	87.4	64.2	23.5
7/20/08	32.4	26.0	4.2	0.0	7.0	89.0	61.9	23.4
7/21/08	32.4	25.5	5.4	0.0	7.3	87.5	60.3	23.7
7/22/08	33.4	26.1	5.4	0.0	7.5	86.0	55.8	22.6
29 week	33.0	25.4	4.9	0.0	7.8	86.8	60.8	23.3
7/23/08	33.7	26.5	5.7	0.0	6.9	84.5	53.8	22.1
7/24/08	33.7	26.0	6.8	0.0	9.0	90.5	63.6	24.4
7/25/08	34.1	24.1	4.4	0.0	5.8	87.3	56.4	22.8
7/26/08	34.2	25.7	5.7	0.0	5.8	81.5	61.3	22.9
7/27/08	34.4	26.0	4.7	0.0	4.2	83.3	66.1	23.5
7/28/08	31.7	24.0	4.0	42.0	3.3	85.6	63.5	24.7
7/29/08	27.0	24.8	0.0	94.2	7.3	95.2	78.3	25.3
30 week	32.7	25.3	4.5	136.2	6.0	86.8	63.3	23.7

Date	Max Temp (°C)	Min Temp (°C)	BSS hrs	RF mm	WS kmph	RH Mor %	RH A/N %	Avg. VP mm of Hg
7/30/08	30.3	25.7	0.0	0.0	8.5	93.5	75.0	25.2
7/31/08	31.6	25.0	2.6	0.0	5.7	75.0	72.4	23.8
8/1/08	31.6	25.7	2.8	0.0	7.0	93.6	72.7	25.7
8/2/08	32.2	25.2	0.5	11.2	2.8	95.1	92.1	24.7
8/3/08	27.4	24.7	2.1	2.0	10.2	91.9	77.2	24.3
8/4/08	30.7	24.9	2.2	22.0	5.0	93.5	82.4	25.0
8/5/08	30.8	25.3	1.0	14.6	7.0	95.1	85.0	25.3
31 week	30.7	25.2	1.6	49.8	6.6	91.1	79.5	24.8
8/6/08	31.2	25.5	0.0	0.0	6.9	91.1	82.2	24.4
8/7/08	29.4	25.0	0.0	1.2	8.3	91.9	69.3	23.2
8/8/08	31.4	24.8	1.0	2.6	10.3	93.5	82.3	24.9
8/9/08	30.7	25.0	0.0	0.0	9.3	93.5	87.6	24.6
8/10/08	28.2	25.0	0.5	1.8	3.5	93.6	74.3	24.4
8/11/08	30.5	26.0	0.6	0.0	10.4	90.4	93.6	24.7
8/12/08	27.4	25.4	0.0	47.2	8.3	95.2	65.8	24.8
32 week	29.8	25.2	0.3	52.8	8.1	92.7	79.3	24.4
8/13/08	26.2	24.5	0.0	41.8	7.2	98.3	77.8	23.6
8/14/08	27.2	24.5	0.0	8.1	15.0	98.3	98.3	24.3
8/15/08	26.0	24.6	0.0	2.6	5.5	96.7	89.2	24.6
8/16/08	28.5	25.3	0.6	0.1	5.1	93.5	71.8	23.7
8/17/08	30.4	24.8	2.1	0.0	5.7	90.2	70.7	22.9
8/18/08	30.9	24.3	7.4	0.0	5.8	93.4	77.2	24.3
8/19/08	30.7	24.5	4.0	0.0	5.7	93.6	68.1	23.8
33 week	28.6	24.6	2.0	52.6	7.1	94.8	79.0	23.9
8/20/08	30.9	24.6	6.2	0.0	6.1	90.1	66.6	21.7
8/21/08	30.8	24.5	3.9	0.0	4.9	88.6	89.0	23.1
8/22/08	30.4	24.0	3.2	6.2	5.6	95.0	63.5	22.7
8/23/08	31.6	24.2	5.4	0.0	3.1	90.2	56.4	21.8
8/24/08	31.8	24.7	7.5	0.0	3.3	88.7	58.7	22.2
8/25/08	32.7	25.2	5.4	0.0	4.2	85.7	89.1	23.7
8/26/08	32.8	26.0	5.2	0.0	4.5	72.3	69.8	21.5
34 week	31.6	24.7	5.3	6.2	4.5	87.2	70.4	22.4
8/27/08	27.8	24.5	0.0	5.1	4.7	95.0	68.5	23.3
8/28/08	29.5	25.0	2.0	1.8	3.0	98.6	66.1	23.8
8/29/08	31.4	25.0	6.0	0.0	4.9	90.3	59.5	22.4
8/30/08	31.6	24.5	9.9	0.0	5.9	82.5	63.3	22.4
8/31/08	32.4	24.6	8.8	0.0	4.9	91.9	52.3	22.5
9/1/08	32.8	25.0	10.7	0.0	2.5	95.6	56.1	25.5
9/2/08	34.4	26.4	9.9	0.0	1.8	89.2	60.4	25.7
35 week	31.4	25.0	6.8	6.9	4.0	91.9	60.9	23.7
9/3/08	35.5	25.7	9.2	0.0	2.6	92.1	59.3	25.2
9/4/08	35.5	26.5	9.7	0.0	2.7	90.7	64.2	26.0
9/5/08	34.5	25.5	7.6	0.0	3.8	89.0	65.9	24.7
9/6/08	33.2	25.2	6.3	0.0	4.2	84.4	62.4	23.4
9/7/08	33.2	25.7	8.9	0.0	4.0	87.4	63.2	23.5
9/8/08	32.7	25.2	7.8	0.0	2.8	90.5	61.0	24.7
9/9/08	34.5	25.5	8.8	0.0	2.8	87.4	62.6	25.1
36 week	34.2	25.6	8.3	0.0	3.3	88.8	62.7	24.7
9/10/08	35.3	26.2	7.5	0.0	3.0	92.1	59.9	24.7
9/11/08	34.4	25.5	5.5	0.0	3.8	90.5	62.4	24.4
9/12/08	33.2	25.4	5.4	0.0	5.6	90.5	60.6	25.5
9/13/08	35.5	26.5	5.9	8.4	3.7	89.0	66.2	25.7
9/14/08	34.4	23.0	8.0	10.2	4.7	96.7	77.5	25.2
9/15/08	31.5	23.0	0.0	6.4	2.0	93.5	92.1	24.6
9/16/08	31.0	24.3	0.5	4.6	4.1	91.8	98.3	23.9
37 week	33.6	24.8	4.7	29.6	3.8	92.0	73.8	24.8
9/17/08	27.5	24.8	0.0	35.4	4.9	90.3	100.0	23.0
9/18/08	27.5	23.5	0.0	117.6	10.0	93.3	95.1	23.7
9/19/08	27.5	24.5	0.0	6.3	6.2	90.3	75.2	25.0
9/20/08	32.1	25.0	4.7	5.6	5.3	93.5	77.5	25.3
9/21/08	32.1	25.3	3.8	0.0	4.2	89.0	67.2	23.7

Date	Max Temp (°C)	Min Temp (°C)	BSS hrs	RF mm	WS kmph	RH Mor %	RH A/N %	Avg. VP mm of Hg
9/22/08	31.5	24.8	7.3	0.0	2.9	77.0	66.5	21.2
9/23/08	30.4	24.5	8.7	0.0	3.2	95.1	69.8	24.1
38 week	29.8	24.6	3.5	164.9	5.2	89.8	78.8	23.7
9/24/08	32.0	24.1	7.1	0.0	2.5	93.5	64.9	23.3
9/25/08	31.8	23.5	9.4	0.0	2.6	86.9	64.8	21.8
9/26/08	31.2	23.3	9.6	0.0	3.7	95.0	63.5	22.3
9/27/08	31.2	23.0	9.4	0.0	4.7	91.7	66.6	21.9
9/28/08	30.5	22.5	9.9	0.0	4.2	87.8	65.5	21.6
9/29/08	31.2	23.0	9.7	0.0	3.5	93.3	62.2	21.7
9/30/08	31.2	23.0	9.0	0.0	3.0	95.0	61.1	21.9
39 week	31.3	23.2	9.2	0.0	3.5	91.9	64.1	22.1
10/1/08	31.6	23.5	7.7	0.0	2.1	91.7	69.0	23.5
10/2/08	32.4	24.1	8.3	0.0	1.6	95.1	71.0	24.3
10/3/08	31.4	25.4	5.8	0.0	2.1	90.3	67.7	25.4
10/4/08	34.2	24.8	8.6	0.0	2.7	95.1	63.7	25.8
10/5/08	35.4	25.0	8.5	0.0	1.4	95.1	62.1	24.7
10/6/08	34.5	24.5	8.6	0.0	4.1	91.9	61.4	23.6
10/7/08	33.5	24.8	7.6	0.0	2.1	90.3	62.4	23.5
40 week	33.3	24.6	7.9	0.0	2.3	92.8	65.3	24.4
10/8/08	33.2	23.5	5.0	0.0	1.5	88.7	59.0	22.6
10/9/08	33.5	23.5	9.2	0.0	2.7	91.9	59.1	23.1
10/10/08	33.5	23.6	9.8	0.0	1.8	88.7	53.1	22.8
10/11/08	35.7	23.4	8.5	0.0	1.9	87.4	48.8	22.7
10/12/08	38.5	23.1	9.4	0.0	1.3	92.0	49.9	23.7
10/13/08	36.6	21.5	9.2	0.0	1.1	84.1	37.9	19.9
10/14/08	37.5	20.7	9.3	0.0	1.0	74.6	37.5	17.6
41 week	35.5	22.8	8.6	0.0	1.6	86.8	49.3	21.8
10/15/08	36.3	20.1	9.7	0.0	1.3	82.1	90.1	20.9
10/16/08	35.5	21.2	9.5	0.0	2.2	88.0	47.7	19.7
10/17/08	35.1	21.6	8.7	0.0	3.0	57.8	50.2	18.1
10/18/08	34.4	21.5	9.4	0.0	2.4	76.9	44.9	18.2
10/19/08	35.2	19.4	9.6	0.0	2.8	76.5	36.7	16.2
10/20/08	35.7	18.2	9.4	0.0	1.5	72.7	30.2	13.9
10/21/08	35.5	17.9	9.6	0.0	2.0	80.8	37.4	15.8
42 week	35.4	20.0	9.4	0.0	2.2	76.4	48.2	17.5
10/22/08	34.8	18.2	9.4	0.0	1.7	68.6	32.8	14.4
10/23/08	35.5	17.6	9.1	0.0	1.8	71.0	31.3	13.9
10/24/08	35.7	18.0	9.3	0.0	1.5	74.8	35.1	15.7
10/25/08	35.8	17.5	8.5	0.0	1.7	79.1	24.0	13.2
10/26/08	35.7	18.2	9.5	0.0	1.7	72.6	26.2	13.0
10/27/08	35.0	17.9	9.4	0.0	2.4	74.6	29.3	14.1
10/28/08	36.2	17.1	9.0	0.0	2.8	84.5	32.5	15.5
43 week	35.5	17.8	9.2	0.0	1.9	75.0	30.2	14.2
10/29/08	34.2	17.2	9.6	0.0	2.8	86.2	33.4	15.9
10/30/08	34.2	17.4	9.5	0.0	3.1	84.5	32.7	15.3
10/31/08	33.6	18.0	9.5	0.0	2.2	74.8	32.9	14.5
11/1/08	33.8	16.8	9.3	0.0	1.5	80.4	27.9	13.7
11/2/08	35.5	16.5	9.3	0.0	1.3	83.8	26.3	13.4
11/3/08	34.8	17.5	9.3	0.0	2.7	78.5	22.9	12.3
11/4/08	35.4	17.0	9.0	0.0	1.3	86.3	25.4	12.4
44 week	34.5	17.2	9.4	0.0	2.1	82.1	28.8	13.9
11/5/08	35.3	17.9	9.6	0.0	3.1	80.3	31.6	14.0
11/6/08	34.3	17.3	9.1	0.0	2.9	90.9	32.5	15.2
11/7/08	34.4	16.0	9.2	0.0	2.4	67.5	28.1	11.6
11/8/08	34.3	16.5	9.5	0.0	3.0	63.5	28.6	11.9
11/9/08	34.6	16.0	9.3	0.0	0.9	86.6	30.0	13.6
11/10/08	35.4	15.8	9.0	0.0	2.1	57.1	29.4	11.0
45 week	33.2	15.5	8.0	0.0	2.8	53.3	18.9	8.1
11/5/08	33.2	14.0	8.7	0.0	2.8	80.5	26.1	11.4
11/6/08	33.5	14.4	8.1	0.0	1.1	88.1	27.7	12.1
11/7/08	32.6	13.4	8.4	0.0	1.1	80.6	25.8	11.4

Date	Max Temp (°C)	Min Temp (°C)	BSS hrs	RF mm	WS kmph	RH Mor %	RH A/N %	Avg. VP mm of Hg
11/8/08	33.4	13.5	8.7	0.0	1.3	76.1	28.1	10.7
11/9/08	32.2	14.0	8.5	0.0	2.1	84.2	34.8	12.8
11/10/08	32.5	17.2	7.9	0.0	2.9	61.7	27.2	9.9
11/11/08	31.8	22.1	7.9	0.0	8.1	56.5	54.8	14.6
46 week	32.7	15.5	8.3	0.0	2.8	75.4	32.1	11.8
11/19/08	29.6	20.7	1.6	0.0	7.8	58.5	55.2	15.4
11/20/08	31.5	17.5	4.3	0.0	2.9	71.1	25.3	10.8
11/21/08	31.9	14.0	9.0	0.0	6.3	42.0	30.4	8.3
11/22/08	30.5	16.5	8.5	0.0	8.6	55.0	35.5	10.4
11/23/08	30.5	15.5	9.1	0.0	7.5	46.8	34.4	9.5
11/24/08	30.8	14.3	9.3	0.0	5.9	55.0	30.6	10.1
11/25/08	32.5	12.1	9.2	0.0	2.3	64.0	28.5	9.9
47 week	31.0	15.8	7.3	0.0	5.9	56.0	34.3	10.6