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Determination of Spring Wheat Response to Developmental Windows Using Simulation Approach

By
Muhammad Asim
M. Phil (Plant Physiology)

DEPARTMENT OF PLANT SCIENCES
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In The Name of
ALLAH,
The Compassionate,
The Merciful

DECLARATION

I hereby declare that the work presented in the following thesis is my own effort, except where otherwise acknowledged, and that the thesis is my own composition. No part of this thesis has been previously presented for my any other degree.

Muhammad Asim

CERTIFICATE

This thesis, submitted by Mr. Muhammad Asim, is accepted in its present form by the Department of Plant Sciences, Quaid-i-Azam University, Islamabad, Pakistan as satisfying the thesis requirements for the degree of Doctor of Philosophy in Plant Physiology.

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Dated: November 12, 2008

Dedicated to
My
Loving Parents,
Wife,
Sons Mobeen, Moeen & Mursaleen

CONTENTS

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Muhammad Asim

LIST OF ABBREVIATIONS

ABBREVIATIONS	COMPLETE DESCRIPTION
°C	Degree Centigrade
GDP	Gross Domestic Production
ESP	Economic Survey of Pakistan
kg	Kilograms
ha	Hectares
CO_2	Carbon Dioxide
°C d	Degree Days
IBSNAT	International Benchmark Sites Network for Agro-technology Transfer
ICASA	International Consortium for Agricultural Systems Applications
DSSAT	Decision Support System for Agro-technology Transfer
APSIM	*A*gricultural *P*roduction *S*ystem S*IM*ulator
SOI	Southern Oscillation Index
ENSO	El Niño Southern Oscillation
NARC	National Agricultural Research Centre
DAP	Di-Ammonium Phosphate
RCBD	Randomized Complete Block Design
MDS	Minimum Data Set
mm	Millimeter
$MJ/M^2/Day$	Milli Joules/Meter square/Day
PMD	Pakistan Meteorological Department
ANOVA	Analysis of Variance
PCCA	Principle Component and Classification Analysis
SD	Standard Deviation
TGW	Thousand Grain Weight
SL	Spike Length
SN	Spikelets Number per Spike
SR	Solar Radiation
CSM	Crop Simulation Model

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ABSTRACT

The present studies were conducted to (a) monitor and correlate crop growth and development to yield, (b) understand genotype x environment x management (G x E x M) interaction, (c) parameterize and evaluate APSIM-Wheat module under local conditions and (d) utilize APSIM simulation model to enhance understanding about the resilience in wheat based cropping system of the area using historical weather data. The studies were carried out at National Agricultural Research Centre (NARC), Islamabad. In this study a series of experiments were conducted using six genotypes (Wafaq-2001, Chakwal-97, NR-55, NR-232, NR-234 and Margalla-99) sown at four sowing dates, started from mid of October and extended until the end of December to cover the whole range of sowing time. These four sowing dates were symbolized as Sowing Windows (SWs) denoted as SW1, SW2, SW3 and SW4. The study was conducted over time (2001-2007) to understand the physiological and ecological aspects of wheat yield over diverse SWs. Crop simulation modeling technique was also used, as a bioinformatics and computational tool to better understand the wheat performance in relation to rainfed environment and to depict tactical management decisions based on such results.

Significant differences were observed in the pattern of biomass accumulation in four SWs across six genotypes. Changes in sowing dates, in the present study, have a negative impact on crop growth rate and a decreasing trend was observed in the biomass accumulation across six genotypes. Among genotypes, NR-234 showed maximum crop growth rate across four SWs. The reduction of 11 % and

39 % was observed for the crop growth rate across genotypes sown in SW3 and SW4 respectively, from SW1 and SW2.

Grain yield reduced in all the genotypes with the change in sowing dates and a yield reduction of 66% was observed in SW4 compared with SW1. Quantification of this yield reduction showed a reduction of about 60 kg/ha/day after SW1 across the genotypes.

Among the parameters analyzed biomass, number of spikelets per spike, and 1000 grain weight were the most important predictors of yield. In the analysis of G x E x M interaction for grain yield, M played a significant contribution towards the grain yield, reflecting the importance of the selection of optimum sowing date in this rainfed area.

*A*gricultural *P*roduction *S*ystems S*im*ulator (APSIM) was used as a bioinformatics tool with its various linked modules performing a number of computations using their inbuilt algorithms. To use this software, it was evaluated and parameterized using wheat crop and climatic data of Islamabad. The advancement in the computational skills of APSIM attributable to the improvement and modification in various cultivar coefficients lead to goodness-of-fit between simulated and measured data regarding the occurrence of anthesis and maturity by accurately regulating the phasic development of the genotypes used in this study. This improvement in the model's ability also improved the simulation capabilities of the model regarding biomass accumulation across sowing windows and yield.

This validated crop simulation model was used to enhance our understanding of crop ecology and physiology and as a tool for selecting optimum sowing date and cultivar. Using it in conjunction with the knowledge of seasonal climate forecasting, using El Niño Southern Oscillation (ENSO)/Southern Oscillation Index (SOI) phases it helped to enhance our knowledge regarding the resilience of cropping system in rainfed area. The simulation analysis regarding partitioning of wheat yield, averaged across SWs, using SOI phases showed that sowing after mid November (SW3 and SW4) was vulnerable to climatic fluctuations governed by SOI phase in July. The analyses also revealed an increased wheat yield of about 1 t/ha in relation with phenomenon of SOI phase 3 (falling) during the month of July as compared to phase 5 (consistently near zero) during the same month and might have a link with the rainfall variability. The analysis using probabilistic approach revealed that, based on long term rainfall data, the Islamabad zone had 44% and 35% possibility of exceeding median rainfall with consistently near zero and consistently negative SOI phases, respectively during July.

Further work is suggested, to link the rainfall variability in this rainfed zone with SOI phases so that the SOI based seasonal forecasting could be used to make decisions for the optimal wheat sowing window and suitable cultivars. It is suggested to organize similar studies on multiple locations to use simulation technique comprehensively as tool for wheat yield forecasts of these areas in relation to SOI phases.

INTRODUCTION

AND

LITERATURE

REVIEW

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Bread wheat (*Triticum aestivum* L.) is the most widely grown crop in the world. Almost one sixth of the total arable land in the world is cultivated with wheat and the area under wheat cultivation is more than 240 million ha (Curtis, 2002). As a food source, and its enormous genetic variability in phenological response to photoperiod and temperature, it is grown in almost all regions of the world in locations ranging in altitude from a few meters to more than 3000 m above sea level (Slafer and Satorre, 2000). Wheat is mainly categorized into spring and winter wheat and refers to the season during which the crop is grown. In winter wheat heading is delayed until the plant experiences a period of cold winter temperatures 0° to 5°C, whereas spring wheat is usually sown in the spring (can be sown in autumn in countries like Pakistan that experience mild winters) and matures during summer (Curtis, 2002).

In Pakistan, wheat is the most important crop being the staple diet and is cultivated on the largest acreages (8.5 million hectares) among cereals in almost every part of the country. It contributes 14.4 percent to the value added in agriculture and 3.0 percent to GDP (Anonymous, 2007). Over the past three decades, increased wheat productivity occurred largely due to the development of high-yielding cultivars and increased fertilizer use (Curtis, 2002). With the introduction of semi-dwarf wheat cultivars, wheat productivity has been increased in all the major cropping systems of rainfed and irrigated areas, representing the diverse and varying agro-ecological suitable conditions (Aslam *et al.*, 1989). However, in a given environment, wheat growth, development and yield depend on suitable cultivars (Grausgruber *et al.*, 2000), management practices and weather conditions (Anda and Antons, 2004).

In Pakistan, wheat is sown over a wide range of sowing date in various cropping systems of rainfed and irrigated areas. This variation in sowing time is caused by various factors such as erratic rainfall, late sowing due to harvesting of preceding crop, lack or unavailability of farm machinery and inputs, etc. The sowing window of wheat in Pakistan generally starts from mid of October and extends until the end of December. Delayed sowing reduces wheat yield almost linearly at the rate of 42 kg/ha/day after optimum sowing time generally quoted as 10^{th} November (Khan, 2003).

Various environmental factors affect wheat growth and development (Altenbach *et al.*, 2003) both in field experiments and controlled chamber experiments (Panozzo and Eagles, 1999; Peterson *et al.*, 1998). Contrasting with responses to photoperiod and vernalization, there are no developmental phases or cultivars insensitive to temperature (Slafer and Rawson, 1995a, 1995b). Other factors, such as level of nutrition (Rodriguez *et al.*, 1994), water availability, plant density and radiation (Rawson, 1993) and CO_2 concentration (Rawson, 1992) also have an effect under varying conditions (Slafer, 1995).

To understand the physiological and ecological aspects of wheat yield, it is necessary to study the physiology of crop development (Slafer *et al.*, 1994a, 1994b). The development of wheat is a continuity of vegetative phase, when the leaves are initiated; the reproductive phase, when floret development occurs until the number of fertile florets is determined; and the grain-filling phase, when the grain first develops the endosperm cells and then grows to determine the final grain weight (Miralles and Slafer, 2000).

Crop phenological stages are important indicators in agricultural production, management, planning and decision-making. For cereal crops, the decimal code system defined by Zadoks *et al.* (1974) has been widely used to record the development stages. The Zadoks stage is a non-linear scale based on irregularly spaced phenological events from sowing to maturity. Using a two-digit code, the Zadoks system can record detailed information about the development status of the plant. These crop phenological events indicate the patterns of its development and are controlled by genetic and environmental factors.

The diversity of responses due to genotype - environment interaction and the information regarding some critical crop developmental phases such as grain filling duration could be exploited by the breeders and crop managers to increase yield potential (Yan and Hunt, 2001; Miralles and Slafer, 2000).

Changes in sowing dates can strongly modify the duration of different developmental phases as the crop is being exposed to varying environmental conditions (Miralles *et al.*, 2001). The effects of any of these environmental factors on crop growth differ depending upon the developmental stages when they act. Developmental responses to temperature start as soon as the seed is imbibed (Roberts, 1988) and continues until maturity (Angus *et al.*, 1981; Porter *et al.*, 1987; Slafer and Savin, 1991).

From the various models that have been proposed to predict the timing of development as affected by temperature, the most widely accepted is the thermal time (with units of degree days, °C d) (Monteith, 1984) which has been widely used in simulation models.

Crop growth simulation models have emerged as a valuable tool for enhancing our understanding of crop ecology and physiology as the knowledge about the research and development of crops has been increasing at a rapid pace. Therefore, the scientists have lumped together the multi-disciplinary knowledge about a crop in the form of Crop Simulation Models (CSM). These models are computer software with mathematical representations of major biological processes and consider systems approach (soil – plant – atmosphere continuum). These models can be utilized to study the impact of several combinations of variables, related to crop, soil, weather, and management, on the growth and yield of a crop, while in the real world such studies will need several years, myriad man-hours, and a lot of time and money (Bouman *et al.*, 1996).

There are two broad classes of crop models: 1) empirical or correlative models which describe relationships between different variables without explaining the underlying physiological or physical causalities, and 2) mechanistic or explanatory models which explicitly describe the relational causality between variables. The mechanistic models take into account the acceptable details of a mechanism or process supported by the underlying causalities (Sridhara and Prasad, 2002; Nestorov *et al.*, 1999; Amir and Sinclair, 1991).

In this computer base information technology era and its usefulness as bioinformatics in agriculture, the application of various crop simulation models, with various algorithms and computational techniques have become accepted tools for agricultural research (Rabbinge, 1986; Seligman, 1990). As field studies conducted to improve the production showed that the results are always season and site specific. A wide variety of crop models has been developed all over the world to serve many different purposes, with major modeling groups in The Netherlands at Wageningen, in the USA in the former project International Benchmark Sites Network for Agro-technology Transfer (Uehara & Tsuji, 1993; Tsuji *et al.*, 1994) now as International Consortium for Agricultural Systems Applications at University of Hawaii with Decision Support System for Agro-technology Transfer (Hoogenboom *et al.*, 2003) and in Australia with the *A*gricultural *P*roduction *S*ystem S*im*ulator (McCown *et al.*, 1996).

*A*gricultural *P*roduction *S*ystems S*im*ulator (*APSIM*), simulates the mechanistic growth of crops, pastures, trees, weeds, dynamics of populations, key soil processes (water, solutes, N, P, carbon, pH), surface residue dynamics & erosion, dryland or irrigated systems, and range of management options considering cropping systems perspective (crop rotations + fallowing + mixtures). APSIM is a software tool that enables sub-models to be linked to simulate agricultural systems (McCown *et al.*, 1996). APSIM has various modules grouped and categorised as plant, environment and management.

APSIM-Wheat module simulates the growth and development of a wheat crop in a daily time-step on an area basis. Wheat growth and development in this module responds to climate, soil water supply and soil nitrogen.

Agricultural production system modeling can be used to answer questions at various levels of aggregation. However, modeling should not be seen as the panacea for all agro-ecological problems but rather as a convenient way of aggregating environmental interactions upon which decisions can be based. Crop modeling integrates our knowledge regarding agricultural systems, and allows generation of information useful for decision makers and highlights gaps in current understanding of the system. It helps in linking agricultural research to tactical management and thus adding value to existing knowledge and research efforts (Meinke *et al.*, 1997).

In the world, several crop models have been developed in research institutes, universities, and agricultural institutions. Some of these models are relatively simple, based on a couple of growth functions, while others are very detailed. Some aim at modeling only certain aspects of crop development while others try to cover as many development processes and environmental relationships as possible (Asseng *et al.*, 2002; Asseng *et al.*, 2000; Meinke *et al.*, 1998). Many models are available and are being used for crops like wheat, maize and other crops.

Parameterization of models is an important task gwhile experimenting with models that focuses the testing of their performance in a wide range of circumstances to identify their scope of validity and their limitations. In an ideal case the model should be validated, that is, tested in the widest possible range of environmental conditions to prove that its built-in relationships and equations hold for any input data set. However, with models detailed enough to claim this capability a relatively complex input data set is required to run the model, and also many field observations are needed to compare model output with reality; and these for a large number of years so that this bioinformatics tool could be used for tactical decision making (Asseng *et al.*, 1998; Meinke *et al.*, 1998).

Seasonal climate forecasts are being increasingly used to aid decision making in agriculture (White, 2000) for risk management under variable climate. Improved skills in seasonal forecasting benefited agricultural management and production. Southern Oscillation Index (SOI) based approach is being progressively used for decision making in northeastern Australia. The SOI phase analysis provided the skill in assessing rainfall probabilities and Hammer (2000) demonstrated how the seasonal forecast information could be used operationally in improving management decisions.

Use of crop simulation models linked with the improved knowledge of seasonal climate forecasting using Southern Oscillation Index (SOI) and El Niño Southern Oscillation (ENSO) allowed the better risk management against climate variability. The phases of the SOI were defined by Stone *et al.* (1996), who used cluster analysis to group two-month pairs of the SOI from 1882 to 1991 into five clusters as phases. The phases are: Phase 1 consistently negative, Phase 2 consistently positive, Phase 3 falling, Phase 4 rising, Phase 5 consistently near zero.

In Pakistan, climate information for the agricultural sector is available for producers from a range of sources. Information is somewhat useful and of interest but lack in providing the level of details needed in order to affect management decisions. To improve climate risk related decision making at the farm level, farmers need to gain a better understanding of the climate factors that affect crop yield in their environment. This will allow decision makers to identify possible management options based on climate information or seasonal climate forecasts.

So, the present study was conducted to improve and enhance the utilization of crop simulation modeling techniques in Pakistan to facilitate agricultural research as a tool for management decision and using it as bioinformatics tool. Specific objectives were to:

1. monitor and correlate crop growth and development to yield,
2. understand genotype x environment x management (G x E x M) interaction,
3. parameterize and evaluate APSIM-Wheat module under local conditions using primary environmental inputs (daily maximum and minimum temperatures, solar radiation, and rainfall), and
4. utilize APSIM simulation model to enhance understanding about the resilience in wheat based cropping system of the area using historical weather data.

MATERIALS AND METHODS

CHAPTER 2

MATERIALS AND METHODS

The present studies were undertaken with the objective to understand the physiological and ecological aspects of wheat yield over diverse sowing windows. The modeling techniques were used as bioinformatics tool to understand biological and environmental phenomenon of crop yield and has proven its efficiency (Seligman, 1990). Therefore, in this study crop simulation modeling technique was used to better understand the wheat performance in rainfed environment.

A series of experiments were conducted on wheat crop to study genotypes' performance over diverse sowing windows. The data so generated was analyzed using various statistical techniques and was also used to parameterize the APSIM model for running the simulations using long term daily weather data. The details of the materials and methods are given as follows:

2.1 EXPERIMENTS

Field experiments on wheat crop were conducted over time starting from 2001-02 crop season and continued up to 2006-07 in the field at National Agricultural Research Centre (NARC), Islamabad (33° 43'N, 73° 06'E and 547 m above sea level). In all the experiments 100 kg/ha each of N and P (as urea and DAP respectively) were applied prior to wheat sowing at different sowing dates. Weed control was done manually. Each year the experiments were laid using Randomized Complete Block Design (RCBD) and the crop was sown with an Aitchison drill in three 4.5 x 10 m plots per sowing window for each cultivar and consisted of 18 rows with row spacing of 25 cm. The experiments, data of which were used for parameterization of APSIM model, were kept free from moisture and nitrogen stresses as wheat growth and development in APSIM-Wheat module respond to the information given by its soil water, soil nitrogen and met modules. Thus testing of the model was done under non-stress conditions which is a pre-requisite of such validation.

2.2 SOWING WINDOWS

Each year the wheat crop was sown at four different sowing dates. The Sowing Windows (SWs) thus created were as follows:

SW1 = Sowing between 15-25 October

SW2 = Sowing between 10-17 November

SW3 = Sowing between 27 November and 02 December

SW4 = Sowing between 10-24 December

The details regarding actual sowing date during each year are given as below:

	Years					
	2001-02	**2002-03**	**2003-04**	**2004-05**	**2005-06**	**2006-07**
Sowing Window 1	October 22	October 20	October 15	October 25	October 20	October 25
Sowing Window 2	November 13	November 15	November 10	November 15	November 17	November 12
Sowing Window 3	November 30	December 02	December 01	November 30	November 30	November 27
Sowing Window 4	December 20	December 24	December 20	December 10	-	December 10

2.3 WHEAT GENOTYPES

Six wheat genotypes were included in the study, among them three are recommended for farmer's cultivation in the area (referred as 'cultivar'), whereas, the other three are the future candidate lines for commercial cultivation (referred as 'potential cultivar') in the study area. The genotypes studied are as follows:

I. Wafaq-2001 (Cultivar)
II. Chakwal-97 (Cultivar)
III. Margalla-99 (Cultivar)
IV. NR-55 (Potential Cultivar)
V. NR-232 (Potential Cultivar)
VI. NR-234 (Potential Cultivar)

The origin of the above mentioned genotypes (in the form of parentage and pedigree) is given below:

S. No.	*Genotype*	*Parentage*	*Pedigree*
1	Wafaq-2001	OPATA/RAYON//KAUZ	CMBW90Y3180-0TOPM-3Y-010M-010M-010Y-1M-015Y-0Y
2	Chakwal-97	BUC`S'/FCT`S'	CM 64663-7M-0Y-0M-7Y-0M.
3	Margalla-99	OPATA/BOW'S'	CM 83398-2M-0Y-0M-5Y-0M
4	NR-55		
5	NR-232	Not released yet	
6	NR-234		

2.4 DATA COLLECTION

The data was collected on various agro-climatic and agronomic aspects according to Minimum Data Set (MDS) described by International Benchmark Sites

Network for Agrotechnology Transfer (IBSNAT) (1988) required for evaluation of model (Ritchie and Otter, 1984).

2.4.1 WEATHER DATA

Data regarding weather prevailed during the study period was collected from the met station located at NARC. The data included maximum and minimum daily air temperature (in °C), precipitation (mm) and sunshine duration (hours).

Long term (1961-2007) weather data for maximum and minimum temperature (in °C), precipitation (mm), sunshine hours and solar radiation ($MJ/M^2/Day$) was collected from Pakistan Meteorological Department (PMD) at Islamabad.

Daily weather data was compiled as a met file under the *A*gricultural *P*roduction *S*ystems S*im*ulator (*APSIM*)-Met module which provided this information to all the APSIM modules in an APSIM simulation.

2.4.2 CROP DATA

2.4.2.1 Phenological Data

Crop phenology data were collected using Zadok's scale (Zadok, 1974) by selecting ten plants per plot for all varieties over various sowing dates. The measurements of the phenological events were started from crop emergence and continued until the crop maturity stage.

2.4.2.2 Biomass

Wheat above ground dry matter (biomass) data was recorded on regular intervals starting from seedling growth at 3 leave stage, anthesis and maturity stages according to the Minimum Data Set (MDS) requirements described by IBSNAT. Sample size consisted of the total plants within 0.25 m x 1 m area. Samples were oven dried at 80°C for 48 hours or until the constant weight is determined.

2.4.2.3 Yield and Yield Components

At maturity number of main stem and head bearing tillers were counted from an area of one meter square. Data regarding plant height, spike length, number of spikelets per spike was also recorded from five plants per plot. This data was averaged across the replicate plots. 1000 grain weight (g) was taken from the harvested sample of one meter square for grain yield.

2.4.3 Soil Data

The soil data for various physico-chemical variables were determined using standard methods described by the IBSNAT (1988). The details regarding soil data are given in Appendix 1. The data was compiled in soil modules of the APSIM model for various calculations within these modules. This information was utilized in APSIM simulations.

2.5 Crop Growth, Development and Yield

Data collected from field experiments conducted during 2001-02 wheat crop season to 2004-05 crop season in the field at NARC, Islamabad was used for this study. All the data was subjected to statistical analysis (Section 2.9).

2.6 GENOTYPE, ENVIRONMENT AND MANAGEMENT INTERACTION

Data collected from all the field trials conducted during 2001-02 wheat crop season to 2006-07 crop season was used to study this interaction. This data was subjected to statistical analysis (Section 2.9). Following was the explanation regarding each component of this interaction.

2.6.1 GENOTYPE (G)

All the genotypes mentioned in Section 2.3 were used in this part of the study.

2.6.2 ENVIRONMENT (E)

Each year from 2001-02 wheat crop season to 2006-07 crop season was treated as a different environment. This was done because of the reason that each year has different environmental conditions and that wheat crop experienced variable environmental conditions every year.

2.6.3 MANAGEMENT (M)

Each SW (mentioned in Section 2.2) was considered as a distinctive management option and used in G x E x M interaction.

2.7 PARAMETERIZATION AND EVALUATION OF APSIM MODEL

2.7.1 THE APSIM MODEL

*A*gricultural *P*roduction *S*ystems *Sim*ulator (*APSIM*) is a software tool that enables sub-models (or modules) to be linked to simulate agricultural systems (McCown *et al.*, 1996). APSIM has various modules grouped and categorised as Plant, Environment and Management. It simulates the mechanistic growth of crops (wheat, mungbean, maize, sorghum, etc.), key soil processes, and range of management options considering cropping systems perspective. *APSIM-Wheat* module simulates the growth and development of a wheat crop in a daily time-step on an area basis (per square meter, not single plant). Wheat growth and development in this module responds to climate, soil water supply and soil nitrogen.

The module returns information on its soil water and nitrogen uptake to the **Soilwat** and **SoilN** modules on a daily basis for reset of these systems. Information on crop cover is also provided to the **Soilwat** module for calculation of evaporation rates and runoff. Wheat stover and root residues are 'passed' from wheat to the surface **Residue** and **SoilN** module respectively at harvest of the crop. The ***SoilN*** module describes the dynamics of both carbon and nitrogen in soil. The APSIM ***Met*** module provided daily meteorological information to all modules within an APSIM simulation.

2.7.2 MODEL PARAMETERIZATION AND EVALUATION

The data collected from the field experiments conducted during 2001-2003 crop growing seasons was used for model evaluation. Model calibration and validation were described as different ways of model evaluation by Otter-Nacke *et al.* (1987). Specific cultivar coefficients for the genotypes used in this experiment were not in the list of genotypes available with the model, therefore, evaluation was done using basic information for the cultivar coefficients provided with the model. The cultivar coefficients were adjusted, until main growth and development stages were simulated within 90% probability of the measured values.

Simulated and observed comparisons were made for growth and development parameters, the purpose being sensitivity analyses of the model and improvement of the coefficients. Coefficients were increased or decreased using a small step if needed (Appendix 2).

2.8 APSIM MODEL UTILIZATION

APSIM was used to study the rainfall variability in the rainfed areas of Islamabad in relation to global mechanisms of El Niño Southern Oscillation / Southern Oscillation Index (ENSO/SOI) and its impact on weather variability in Pakistan. To study the impact of ENSO/SOI phases on rainfall variability in this area, attempt was made to establish a relationship between rainfall variability during October-November (start of sowing window) and monthly SOI phase in July (selected on the basis of rainfall data analysis). A probabilistic approach was used to describe the chances of exceeding median rainfall. The median rainfall was calculated from the long term (1961-2007) actual rainfall data.

Rainfall data (1961 - 2007) was analyzed using STATISTICA version 6 (StatSoft, 2001) by plotting the total monthly actual rainfall received over that period of time to get the pattern in Islamabad during summer (*locally called as kharif season starting from June and extended until September*) and winter (*locally known as rabi season, the duration of which is from October to May*) seasons (1961-2007). Actual rainfall data was aggregated over a span of 3 years. Range of deviation from 3 years' mean was also calculated against each aggregated value.

APSIM-wheat module, which had been evaluated and parameterized for Islamabad region, was used to simulate wheat crop using long term (1961-2007) climatic data. Yield data thus generated was then averaged across sowing windows and genotypes. The averaged yield data was partitioned on the basis of July SOI phase. The purpose of this partitioning was to explore the use of seasonal climate forecasting based on SOI phase for the selection of optimum sowing time and suitable cultivar.

2.9 STATISTICAL ANALYSIS

Analysis of variance (ANOVA) was performed to test the significant differences between means of various parameters studied for six genotypes across four Sowing Windows (SWs) during 2001-02 to 2004-05 wheat growing seasons. However, for G x E x M interaction study analysis was done across six years (2001-02 to 2006-07 wheat growing seasons). The ANOVA was also performed to find the significance of the effects by G, E, M, and all possible interaction on yield and other parameters.

Multiple regression analysis and correlation analysis were performed to show the relationship of various parameters with yield and the direct and indirect effects of these parameters on yield.

To find out the best and worst performance of a genotype percent difference between individual genotype mean across all sowing windows and mean of all genotypes in a year was calculated.

Principle Component and Classification Analysis (PCCA) was performed to study the relationship of six genotypes with environmental variables, years and sowing windows for yield.

Means and standard deviations of the measured and simulated values were calculated and used to evaluate the effectiveness of the model in estimating phenology (anthesis and maturity, in *Days after Sowing*), grain yield and biomass (in kg/ha). Performance of the model was also evaluated by regressing simulated and measured values and variation was determined using the coefficient of determination (r^2). T-test was also performed to determine the significance of differences between simulated and observed values.

Analysis of variance (for G x E x M) was performed using MSTATC version 1.42 (Freed and Eisensmith, 1991), while all other analysis including some basic statistics were performed using STATISTICA version 6 (StatSoft, 2001).

RESULTS

CHAPTER 3

RESULTS

The rainfed agriculture prevails in about 20 % of the total area under wheat cultivation in Pakistan (Anonymous, 2007). In rainfed areas the wheat productivity mainly depends on the moisture conserved during the preceding summer (monsoon) season or the moisture received during the crop growing season. However, the wheat establishment mainly depends on the moisture available at the time of sowing in the upper profile of the soil. The weather conditions during monsoon and at the time of sowing play a pivotal role in this regard. The understanding of best match between sowing time and weather condition could help in decision making for the farmers regarding suitable time of sowing under rainfed conditions. The presented are the results of the studies using simulation modeling technique to depict tactical management decisions based on such results.

3.1 PERFORMANCE OF WHEAT GENOTYPES OVER SOWING TIMES REGARDING BIOMASS ACCUMULATION

3.1.1 BIOMASS ACCUMULATION RATE IN DIFFERENT GENOTYPES OVER SOWING WINDOWS

3.1.1.1 Biomass accumulation in genotypes during SW1

*An*alysis of *Va*riance (ANOVA) revealed that the differences among wheat genotypes under study were significant (P < 1% level) regarding biomass accumulation rate (Appendix 3) at various crop growth stages. Table 3.1 revealed that the biomass accumulation rate at 3 leaf stage, (from 3 leaf stage to) anthesis, and (from anthesis to) maturity differ significantly among the wheat genotypes.

Among the wheat genotypes sown in mid of October (SW1), maximum biomass accumulation at 3 leaf stage was observed in NR-232 and Margalla-99 at an accumulation rate of 1.19 g/m^2/day (Table 3.1). Margalla-99 showed a higher rate of biomass accumulation (12.94 g/m^2/day) followed by Chakwal-97 (12.86 g/m^2/day) at anthesis, calculated between 3 leaf stage and anthesis. Among others, NR-234 (12.57 g/m^2/day) showed biomass accumulation at a higher rate (Figure 3.1) at anthesis (Table 3.1) when sown in SW1.

Table 3.1 Pattern of biomass accumulation (g/m^2/day) in wheat genotypes under SW1

	Wafaq -2001	Chakwal -97	NR-55	NR-232	NR-234	Margalla -99	F Value
At 3 leaf stage	1.14 b	1.10 c	1.00 d	1.19 a	1.14 b	1.19 a	61.91***
At Anthesis	9.32 d	12.86 a	8.57 e	9.58 c	12.57 b	12.94 a	5817.97***
At Maturity	6.56 c	0.20 e	6.77 b	7.98 a	0.19 e	0.50 d	19867.81***

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level,
* Significant at $P < 10\%$ level, NS= Non-Significant
All such values, which share a common English letter, are non-significantly different; otherwise they differ significantly at $P < 5$ % level

Significant (at $P < 5$ % level) differences were observed in the biomass accumulation rate at maturity (calculated during anthesis and maturity) among the genotypes sown in SW1. NR-232 attained maximum accumulation rate (7.98 g/m^2/day) followed by NR-55 (6.77 g/m^2/day) and Wafaq-2001 (6.56 g/m^2/day). Biomass accumulation rate of Chakwal-97 and NR-234, which showed a higher accumulation rate among genotypes at anthesis reduced significantly (at $P < 5$ % level) and were the lowest (below 0.20 g/m^2/day) among genotypes.

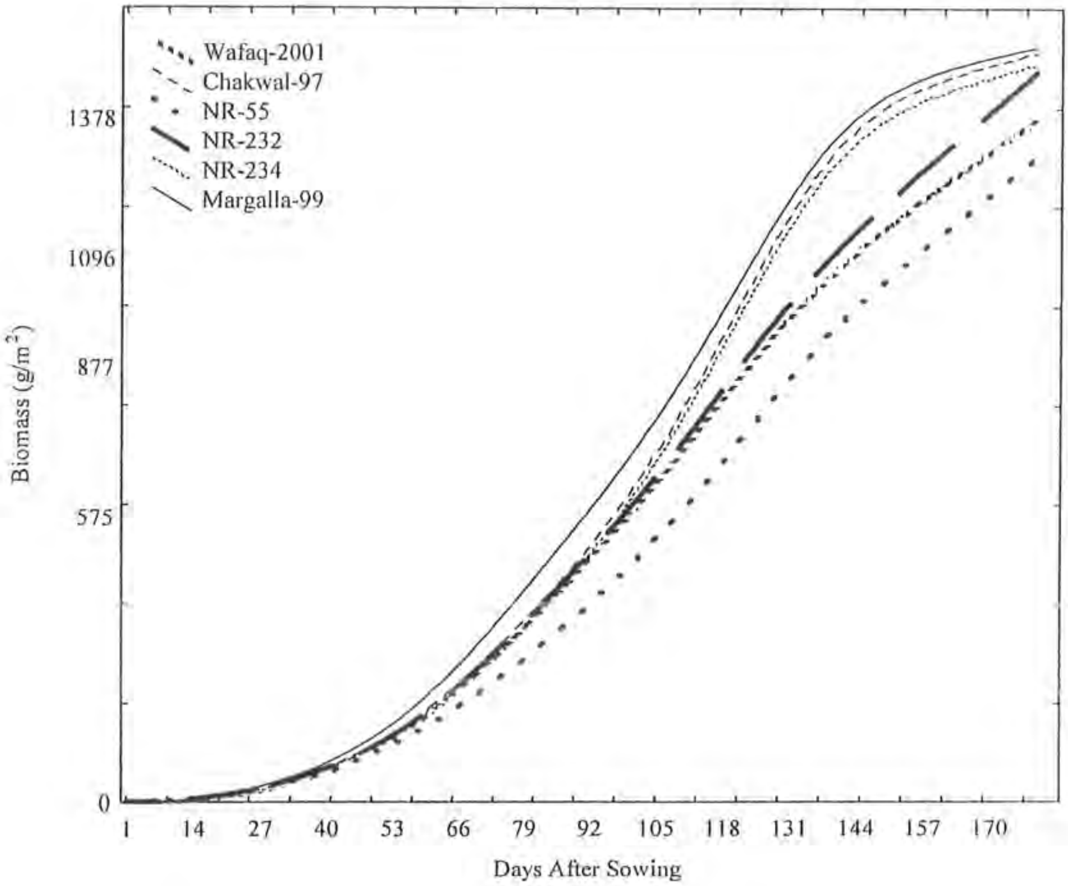

Figure 3.1 Pattern of biomass accumulation in six genotypes sown in SW1

These differences regarding biomass accumulation rate among genotypes lead to non-significant differences in total above ground biomass at maturity among six wheat genotypes (Appendix 8). It clearly showed that on SW1 among all the genotypes under study, the biomass accumulation rate varied at various growth stages however; at maturity all the genotypes attained the potential biomass under the given environment.

The data presented in Appendix 9 revealed that in SW1, Margalla-99 showed maximum total above ground biomass at maturity (15133 kg/ha with Standard Deviation (SD) of 961 kg/ha) while NR-55 showed 14505 kg/ha of total above ground biomass (SD 1631 kg/ha) at maturity and was the lowest among the six genotypes under study.

3.1.1.2 Biomass accumulation in genotypes during SW2

ANOVA (Appendix 4) revealed that wheat genotypes sown in SW2 showed significant differences (at $P < 1\%$ level) in biomass accumulation rate among the genotypes at 3 leaf stage and at anthesis (during anthesis to maturity period). However, at anthesis, genotypic differences were statistically non-significant (Appendix 4).

Among the wheat genotypes sown in SW2, at 3 leaf stage maximum biomass accumulation rate was observed in NR-234 (1.22 $g/m^2/day$) while Wafaq-2001 accumulated at a rate of 0.70 $g/m^2/day$ and was the lowest among these genotypes (Table 3.2).

Table 3.2 Pattern of biomass accumulation ($g/m^2/day$) in wheat genotypes under SW2

	Wafaq-2001	Chakwal-97	NR-55	NR-232	NR-234	Margalla-99	F Value
At 3 leaf stage	0.70 e	0.93 d	0.93 d	1.07 c	1.22 a	1.11 b	216.70***
At Anthesis	12.13 a	12.40 a	11.93 a	12.57 a	12.83 a	13.36 a	1.59NS
At Maturity	1.98 c	1.64 e	1.29 f	2.64 a	2.29 b	1.88 d	1239.36***

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level,
* Significant at $P < 10\%$ level, NS= Non-Significant
All such values, which share a common English letter, are non-significantly different; otherwise they differ significantly at $P < 5$ % level

Biomass accumulation rate at anthesis (from 3 leaf stage to anthesis) was observed maximum in Margalla-99 (13.36 $g/m^2/day$) (Table 3.2). Amongst others, accumulation rate varied between 11.93 $g/m^2/day$ (NR-55) and 12.83 $g/m^2/day$ (NR-234), but the genotypic differences regarding biomass accumulation rate at anthesis (during 3 leaf stage to anthesis) the differences were statistically ($P < 5$ % level) non-significant among all these genotypes (Appendix 4).

At maturity, a decrease in accumulation rate was observed (during anthesis to maturity period) for Wafaq-2001, NR-55 and NR-232 as compared to SW1 (Table 3.1 and Table 3.2), while Chakwal-97, NR-234 and Margalla-99 showed higher accumulation rate in SW2 (Table 3.2). Biomass accumulation rate at maturity (during anthesis to maturity) differ significantly (at $P < 5$ % level) among these genotypes with NR-232 showed maximum accumulation rate (2.64 $g/m^2/day$) while NR-55 showed the lowest accumulation rate (1.29 $g/m^2/day$) under SW2 (during anthesis to maturity period) at maturity (Table 3.2 and Figure 3.2).

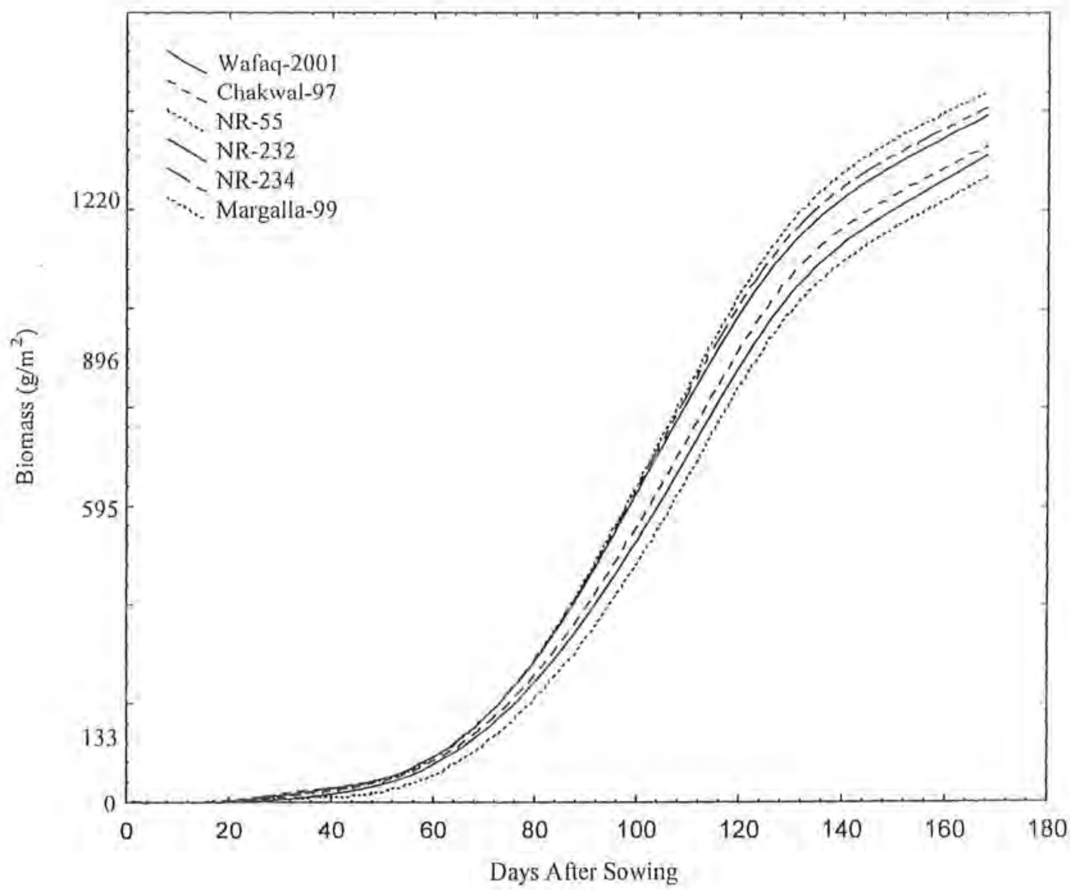

Figure 3.2 Pattern of biomass accumulation in six genotypes sown in SW2

ANOVA (Appendix 8) revealed that the genotypic differences were statistically non-significant (at $P < 1\%$, $P < 5\%$ and $P < 10\%$ levels) among these genotypes under study regarding total above ground biomass at maturity.

The data presented in Appendix 10 revealed that in SW2, Margalla-99 again showed maximum total above ground biomass at maturity (13322 kg/ha with SD of 747 kg/ha). NR-55 demonstrated the lowest biomass accumulation 12180 kg/ha (SD 1584 kg/ha) at maturity but all the genotypes showed non-significant differences (at $P < 1\%$, $P < 5\%$ and $P < 10\%$ levels) regarding biomass at maturity (Appendix 8).

3.1.1.3 Biomass accumulation in genotypes during SW3

Analysis of Variance (ANOVA) revealed that the biomass accumulation rate among these genotypes differ significantly ($P < 1\%$ level) at 3 leaf stage, (from 3 leaf stage to) anthesis, and (from anthesis to) maturity (Appendix 5).

All the wheat genotypes sown in SW3 showed the lowest accumulation rate until 3 leaf stage and were observed below 0.36 $g/m^2/day$ (Table 3.3). Genotypic differences weie statistically significant ($P < 5\%$ level) at 3 leaf stage. At anthesis (from 3 leaf stage to anthesis) a sharp increase was observed in these genotypes (Figure 3.3). NR-234 showed maximum accumulation rate of (14.48 $g/m^2/day$) while NR-232 showed the lowest rate of biomass accumulation (11.88 $g/m^2/day$). Significant ($P < 5\%$ level) differences were observed in the total above ground biomass at maturity among all the genotypes sown in SW3. NR-234 again attained maximum accumulation rate (7.00 $g/m^2/day$) while the

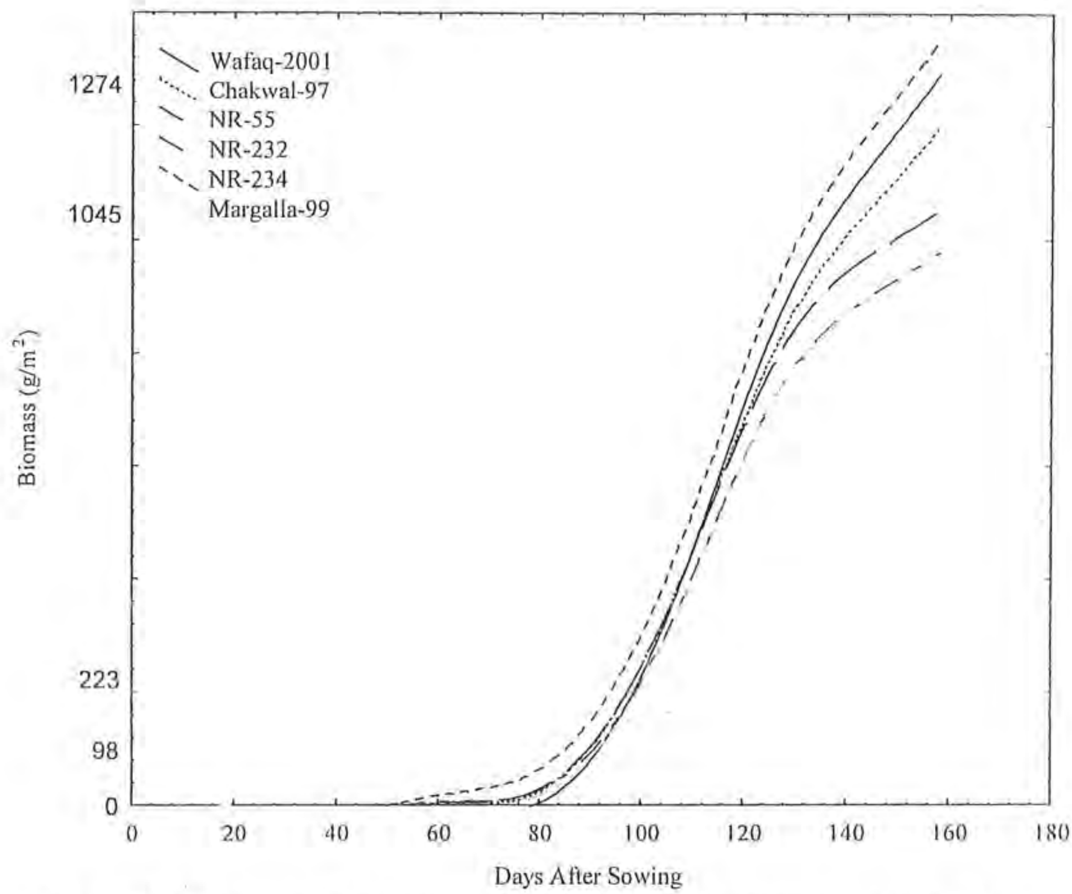

Figure 3.3 Pattern of biomass accumulation in six genotypes sown in SW3

accumulation rate in case of Margalla-99 decreased to the lowest value of 1.52 g/m^2/day among these genotypes sown in SW3 (Table 3.3).

Means presented in Appendix 11 revealed that in SW3, NR-234 showed maximum total above ground biomass at maturity (10346 kg/ha with SD of 1054 kg/ha) and Margalla-99 showed the lowest among these genotypes when sown in SW3 (9557 kg/ha with SD of 1067 kg/ha). However, the genotypic differences regarding total above ground biomass at maturity among six genotypes under study were non-significant (Appendix 8) at any level of significance ($P < 1\%$, $P < 5\%$ and $P < 10\%$ levels).

Table 3.3 Pattern of biomass accumulation (g/m^2/day) in wheat genotypes under SW3

	Wafaq-2001	Chakwal -97	NR-55	NR-232	NR-234	Margalla -99	F Value
At 3 leaf stage	0.24 c	0.24 c	0.22 d	0.26 b	0.36 a	0.26 b	20.64***
At Anthesis	13.77 b	12.88 c	12.89 c	11.88 d	14.48 a	11.91 d	2302.02***
At Maturity	6.94 a	6.18 b	1.73 c	1.73 c	7.00 a	1.52 d	12695.45***

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level,
* Significant at $P < 10\%$ level, NS= Non-Significant
All such values, which share a common English letter, are non-significantly different; otherwise they differ significantly at $P < 5$ % level

3.1.1.4 Biomass accumulation in genotypes during SW4

The performance of wheat genotypes regarding biomass accumulation rate revealed significant differences ($P < 1\%$ level) (Appendix 6) at various crop growth stages. Among the genotypes under study, NR-232, NR-234 and Margalla-99 exhibited maximum accumulation rate (0.54 g/m^2/day) and differ significantly

($P < 5\%$ level) with other genotypes at 3 leaf stage (Table 3.4). Wheat genotypes sown in SW4 also exhibited differences in the pattern of biomass accumulation (Figure 3.4) at anthesis and maturity.

In SW4, the biomass accumulation rate remained low and the maximum rate at 3 leaf stage was 0.54 $g/m^2/day$ achieved by NR-232, NR-234 and Margalla-99 (Table 3.4). At (from 3 leaf stage onward to) anthesis, maximum rate was attained by NR-234 (7.01 $g/m^2/day$). At maturity, the accumulation rate was enhanced by all the genotypes except Chakwal-97 (3.21 $g/m^2/day$). Maximum accumulation rate was attained by NR-234 (9.71 $g/m^2/day$) for this period in SW4.

Table 3.4 Pattern of biomass accumulation ($g/m^2/day$) in wheat genotypes under SW4

	Wafaq-2001	Chakwal-97	NR-55	NR-232	NR-234	Margalla-99	F Value
At 3 leaf stage	0.49 ab	0.46 b	0.44 b	0.54 a	0.54 a	0.54 a	8.90***
At Anthesis	5.87 d	5.59 f	5.80 e	6.36 c	7.01 a	6.62 b	1107.51***
At Maturity	7.36 d	3.21 f	7.04 e	9.21 b	9.71 a	8.64 c	94205.25***

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level,
* Significant at $P < 10\%$ level, NS= Non-Significant
All such values, which share a common English letter, are non-significantly different; otherwise they differ significantly at $P < 5$ % level

Analysis of Variance (ANOVA) revealed that the total above ground biomass at maturity in six genotypes under study differ non-significantly among these genotypes (Appendix 8) at any level of significance ($P < 1\%$, $P < 5\%$ and $P < 10\%$ levels). The data presented in Appendix 12 revealed that in SW4, NR-234 showed maximum average above ground biomass at maturity (8258 kg/ha). The

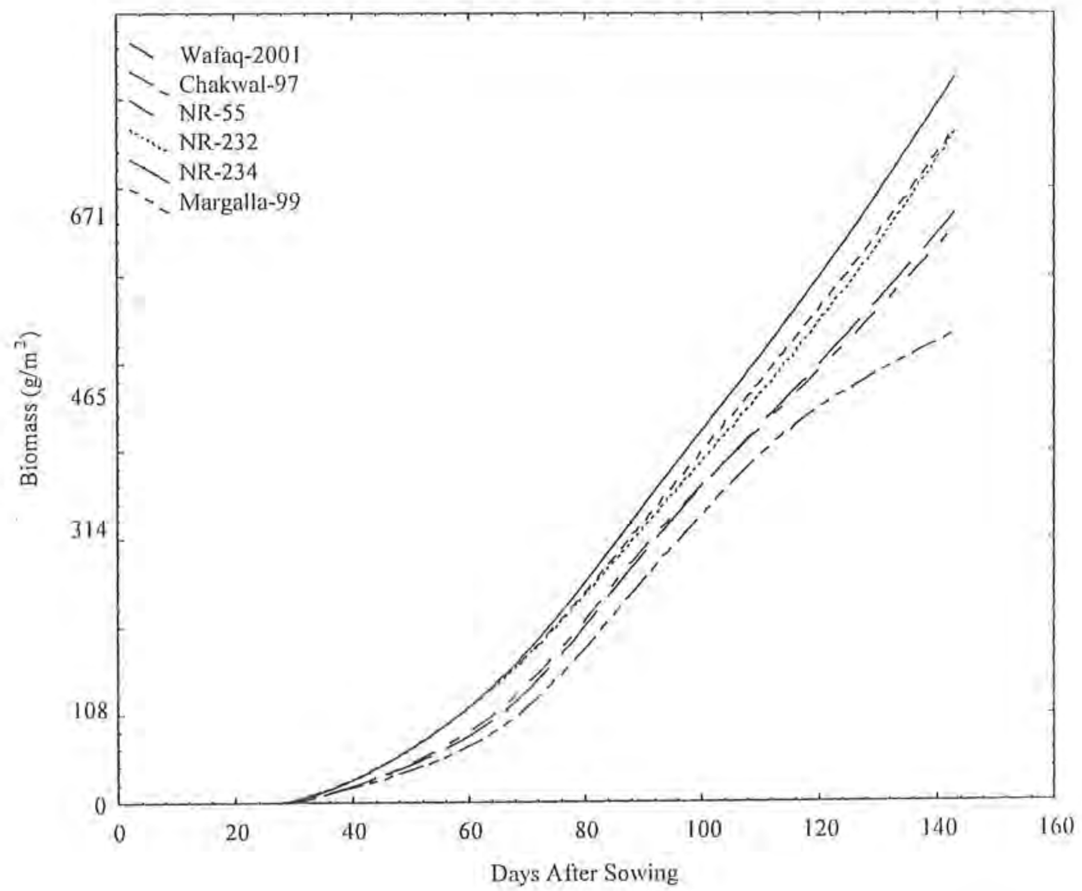

Figure 3.4 Pattern of biomass accumulation in six genotypes sown in SW4

value of SD was observed as 3672 kg/ha and showed the variability and vulnerability of wheat crop sown in SW4. Chakwal-97 accumulated the lowest biomass at maturity (5334 kg/ha with SD of 3055 kg/ha) among the six genotypes under study (Appendix 12).

3.1.1.5 Biomass accumulation in genotypes across SWs

Significant differences were observed in the pattern of biomass accumulation in four SWs across the six genotypes (Figure 3.5). ANOVA revealed significant differences among the genotypes under study regarding biomass accumulation rate at 3 leaf stage, (from 3 leaf to) anthesis, and (from anthesis to) maturity across SWs (Appendix 7).

Changes in sowing time have a negative impact on crop growth rate regarding biomass accumulation. Overall, the reduction of 11% and 39% was observed for the biomass accumulation rate when sown in SW3 and SW4 respectively, from SW1 and SW2 (Appendix 13).

The biomass accumulation rate averaged across SWs revealed that NR-234 achieved maximum accumulation rate at 3 leaf stage (0.82 g/m^2/day) and at anthesis (11.72 g/m^2/day during 3 leaf stage to anthesis period) while Wafaq-2001 showed highest accumulation at maturity (5.71 g/m^2/day), calculated from the time taken during anthesis and maturity. Contrary to this, NR-55 (0.65 g/m^2/day) and Chakwal-97 (2.75 g/m^2/day) showed lowest biomass accumulation rate at 3 leaf stage and at maturity respectively (Table 3.5).

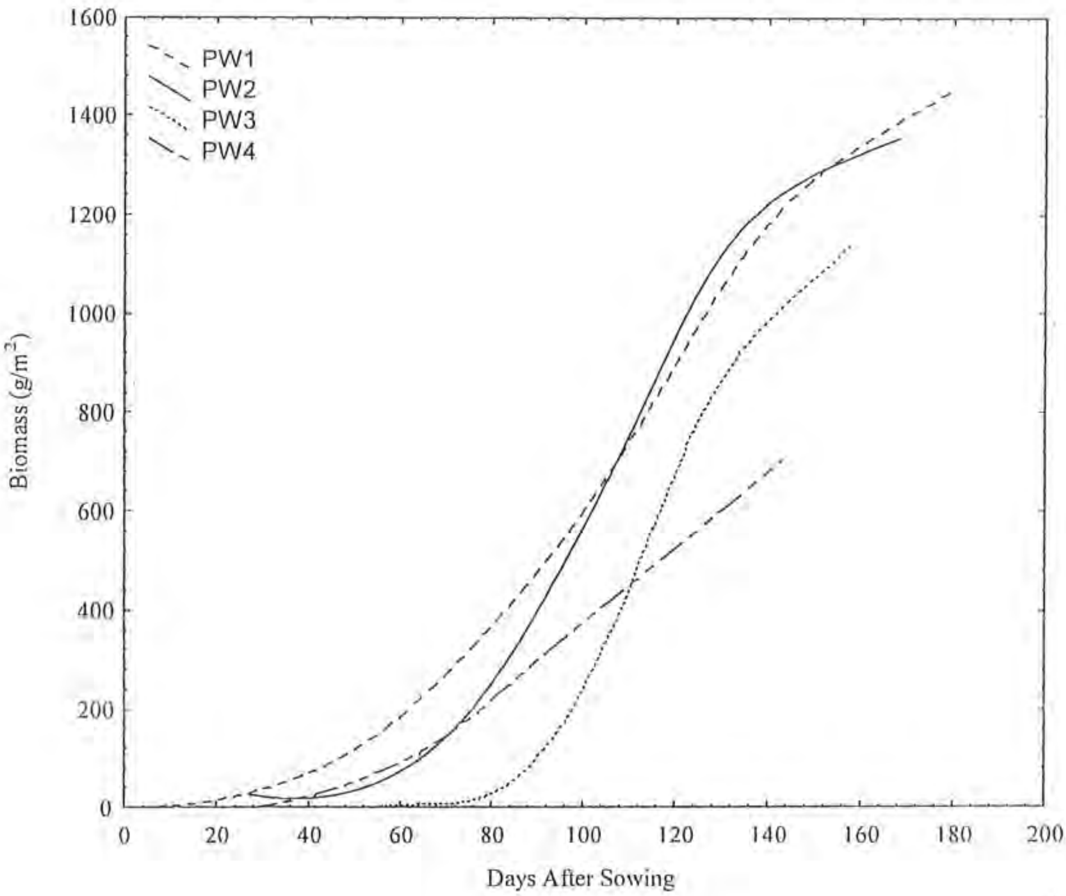

Figure 3.5 Pattern of biomass accumulation across six genotypes sown in four SWs

Among the six wheat genotypes, NR-234 accumulated biomass at the highest across SWs while NR-55 showed the lowest biomass accumulation rate (Appendix 13) and revealed a reduction of 16 % in the rate of biomass accumulation during the crop's life cycle. This shows that NR-234 was resilient to the change in environmental factors during the course of crop development.

Analysis of Variance (ANOVA) revealed that the total above ground biomass at maturity differ non-significantly among genotypes (Appendix 8) at any level of significance (P < 1% level, 5% level, 10% level). However, ANOVA for six genotypes showed significant differences (P < 1 % level) for biomass at maturity when the crop was exposed to variable environmental conditions by sowing in variant SWs and diverse years (Appendix 8)

The data presented in Appendices 9-12 revealed that maximum mean above ground biomass was achieved by Margalla-99 (15133 kg/ha) in SW1 while lowest was achieved by Chakwal-97 (5334 kg/ha) in SW4 among the six genotypes under study. Appendix 20 showed that in most of the cases the observed biomass varied between 800 g/m^2 to 1600 g/m^2 across four SWs with the lowest observed biomass of 200 g/m^2 and highest biomass of 2200 g/m^2.

A decreasing trend was observed in the biomass accumulation across the six genotypes with change in sowing time. A decrease of about 6%, 22% and 51% was observed in biomass from SW1 to SW2, SW3 and SW4 respectively (Appendices 9-12).

Table 3.5 Pattern of biomass accumulation (g/m²/day) in wheat genotypes averaged across SWs

	Wafaq-2001	Chakwal-97	NR-55	NR-232	NR-234	Margalla-99	F Value
At 3 leaf stage	0.64 b	0.68 b	0.65 b	0.77 a	0.82 a	0.78 a	31.56 ***
At Anthesis	10.27 d	10.93 c	9.80 f	10.10 e	11.72 a	11.21 b	7472.57***
At Maturity	5.71 a	2.75 f	4.20 d	5.39 b	4.80 c	3.01 e	5697.88***

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level,
* Significant at $P < 10\%$ level, NS= Non-Significant
All such values, which share a common English letter, are non-significantly different; otherwise they differ significantly at $P < 5$ % level

3.2 YIELD AND YIELD COMPONENTS

3.2.1 PLANT HEIGHT

Analysis of Variance (ANOVA) for testing the variations between mean plant height among six genotypes sown in four SWs over a period of four years (2001-02 to 2004-05 crop seasons) revealed that plant height gained by the wheat genotypes differ significantly ($P < 1\%$ level) with changes in SW and years (Appendix 8). ANOVA results also indicated that about 90% of the variation in plant height of these genotypes sown over four SWs was due to the changes in sowing time (Appendix 8).

In SW1, maximum plant height was attained by NR-232 (112 cm with SD of 5 cm) while minimum plant height was observed in case of NR-234 (109 cm with SD of 1 cm) (Appendix 9).

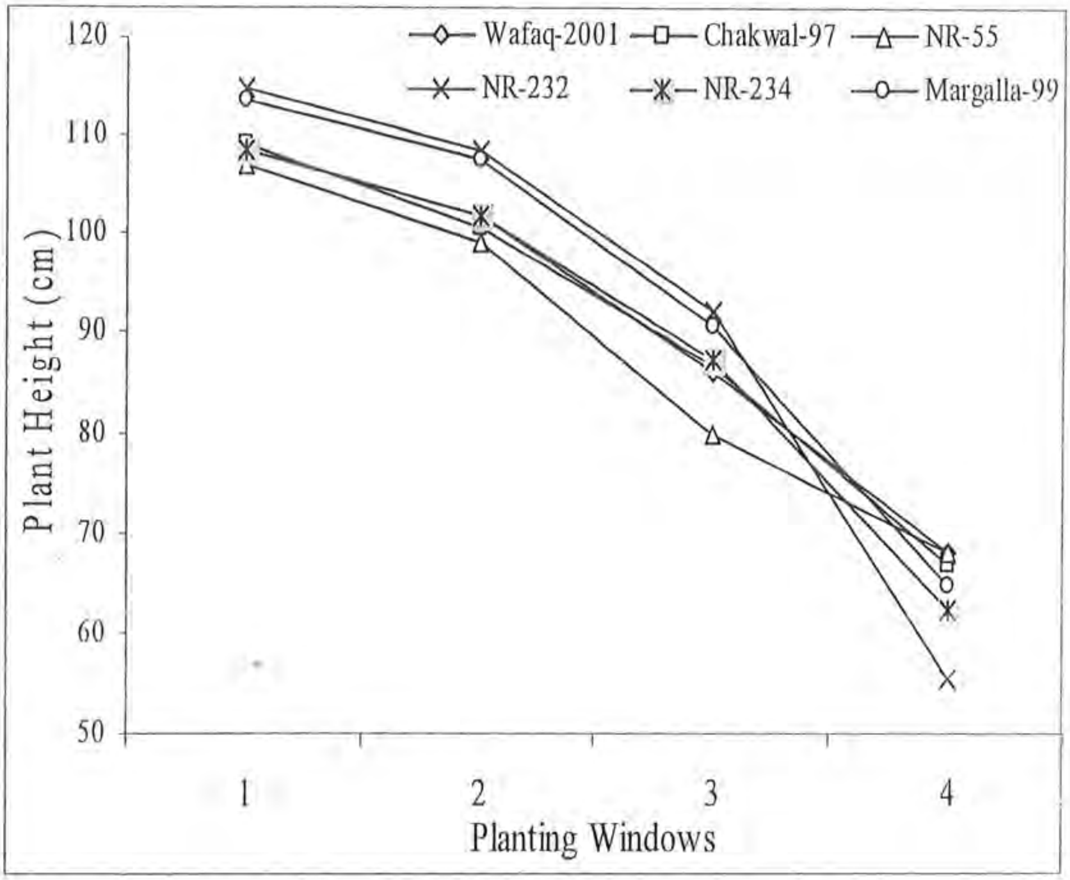

Figure 3.6. Wheat plant height (cm) as affected by sowing windows

Margalla-99 gained maximum plant height of 104 cm (SD of 7 cm) in SW2 while Chakwal-97 showed minimum plant height of 100 cm (SD of 4 cm) (Appendix 10). Comparing the two SWs, plant height was reduced (Figure 3.6) by 6 % from SW1 to SW2.

Among the six genotypes sown in SW3, maximum plant height was attained by Wafaq-2001 (95 cm with SD of 12 cm) and lowest by NR-234 (88 cm with SD of 7 cm) (Appendix 11). Thus a reduction of 21 % was observed in plant height across genotypes from SW1 to SW3.

Wheat genotypes sown in SW4 showed a reduction of 42 % regarding plant height from SW1. Appendix 12 showed that maximum plant height was observed in NR-234 (84 cm with SD of 15 cm) while the lowest was observed for Chakwal-97 (74 cm with SD of 12 cm).

With the changes in SW, plant height reduced linearly (Figure 3.6) from 112 cm (SD of 5 cm) for NR-232 in SW1 (Appendix 9) to 74 cm in SW4 for Chakwal-97 (SD of 12 cm) (Appendix 12). Data presented in Appendix 16 showed that most of the observations regarding plant height varied between 90 cm and 115 cm.

3.2.2 SPIKE LENGTH

Analysis of Variance (ANOVA) given in Appendix 8 revealed that spike length differs significantly among the genotypes under study ($P < 5\%$ level). Changes in spike length due to the change in sowing time from SW1 to SW4 were also significant ($P < 1\%$ level) and explained 55% of the variation in spike length (Appendix 8).

In SW1, spike length varied between 10.0 cm (for Wafaq-2001 with SD of 0.8 cm) and 10.9 cm (for Chakwal-97 with SD of 0.5 cm and for NR-234 with SD of 0.6 cm) (Appendix 9), while in SW2 spike length varied between 10.5 cm (for NR-234 with SD of 0.6 cm) and 10.9 cm (for NR-232 with SD of 0.6 cm) (Appendix 10).

In SW3, maximum spike length was observed for NR-234 (10.9 cm with SD of 0.4 cm) and NR-232 (10.9 cm with SD of 0.8 cm), while Wafaq-2001 showed minimum spike length of 10.0 cm (with SD of 0.8 cm) (Appendix 11). In SW4, spike length varied between 9.9 cm for Wafaq-2001 and Chakwal-97 (with SD of 0.4 cm and 0.8 cm respectively) and 10.2 cm for NR-234 (with SD of 0.6 cm) (Appendix 12).

Wheat genotypes varied in spike length between 10 and 11 cm with variant sowing time across SWs (Appendix 17). Among the genotypes, NR-234 and NR-232 were the most sensitive to change in sowing time (Figure 3.7) regarding spike length.

3.2.3 Spikelet Number per Spike

Analysis of Variance (ANOVA) revealed that number of spikelets per spike varied significantly ($P < 1\%$ level) with the variant sowing time over years. Genotypic differences regarding number of spikelets per spike were non-

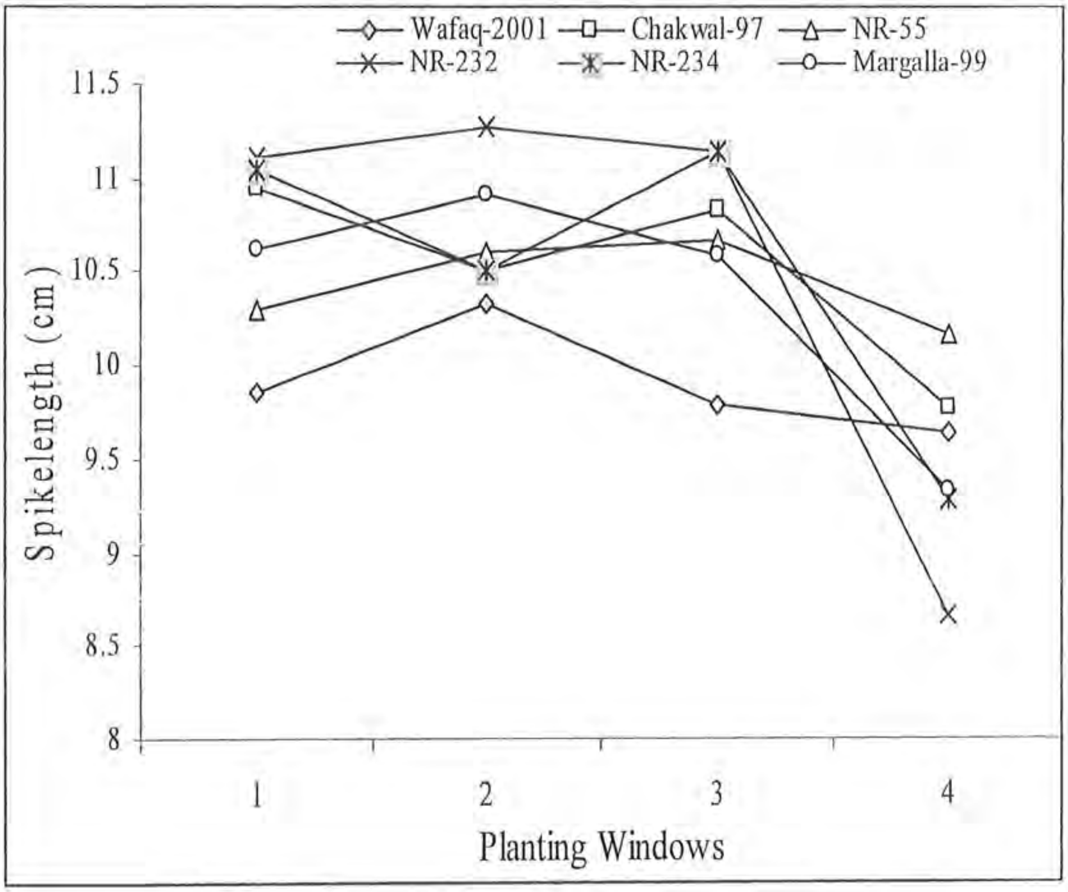

Figure 3.7 Wheat spike length (cm) as affected by sowing windows

significant (Appendix 8). Of the observed variation in number of spikelets per spike among wheat genotypes, 76 % variation was observed mainly due to SWs.

In SW1, maximum number of spikelets per spike was observed in Margalla-99 (20.5 with SD of 2.1) while Wafaq-2001 gained lowest number of spikelets per spike (19.4 with SD of 1.3) (Appendix 9). Data presented in Appendix 10 revealed that in SW2 more than 20 spikelets per spike were observed among genotypes under study with Chakwal-97 achieving maximum number of spikelets per spike (20.8, SD 1.2). However, in SW3 number of spikelets varied between 19.1 and 20.1 (Appendix 11) among the genotypes and in SW4, it varied from 18.0 to 18.5 (Appendix 12). Most of the observations regarding spikelets number per spike varied between 18 and 21 spikelets per spike (Appendix 18).

Figure 3.8 showed that significant differences were observed only in SW4 with 15 % reduction in number of spikelets from that of SW1. Among SW1, SW2 and SW3 the variations were less than 2 %. NR-55 showed the minimum effect of sowing time on spikelets whereas, NR-232 showed the maximum reduction in number of spike lets per spike (Appendices 9-12).

3.2.4 TILLER PER m^2

The results of Analysis of Variance (ANOVA) for tillers per m^2 revealed that significant ($P < 1\%$ level) variation was observed in number of tillers due to change in sowing time (Appendix 8). The variation in sowing time accounted for 88 % regarding variation in tiller production. The data collected each year also differ significantly at $P < 1\%$ level and indicated 8% of variations in number of

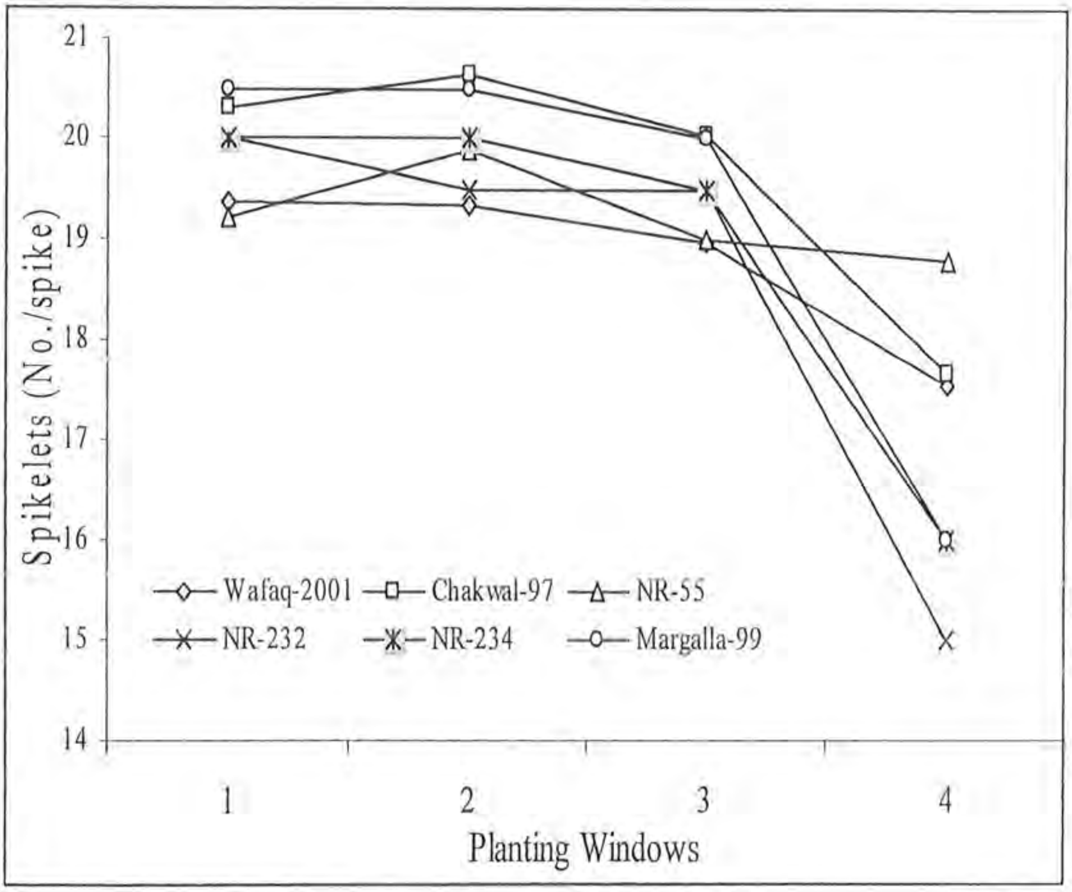

Figure 3.8 Number of spikelets per spike of wheat as affected by sowing windows

tillers among years under study. The genotypic differences, however, were non-significant (Appendix 8).

Changes in sowing time significantly reduced the number of tillers per m^2 counted at maturity (Appendix 8) in all the genotypes. The trend in reduction of number of tillers per m^2 was similar and linear (Figure 3.9) in all the genotypes but the differences among genotypes regarding number of tillers per m^2 were non-significant (Appendix 8). Chakwal-97 exhibited maximum number of tillers among the genotypes in SW1 (375 per m^2 with SD of 24 per m^2) while NR-232 showed minimum tiller production of 319 per m^2 with SD of 37 per m^2 (Appendix 9).

Margalla-99 produced maximum tillers in SW2 (305 per m^2 with SD of 43 per m^2) (Appendix 10). Data presented in Appendix 11 revealed that Chakwal-97 achieved maximum tillers per m^2 in SW3 (236 per m^2 with SD of 58 per m^2). NR-234 produced maximum tillers per m^2 in SW4 (181 per m^2 with SD of 92 per m^2) (Appendix 12). Generally, most of the observations varied between 150 - 350 tillers per m^2 (Appendix 19).

Late sowing of wheat resulted in reduced number of tillers per m^2 counted at maturity and a reduction up to 79 % was observed in SW4, 43 % in SW3 and 15 % in SW2 from the number of tillers in SW1 across genotypes. Among all the genotypes, Margalla-99 was more prone to change in sowing date and showed maximum reduction in number of tillers with the variant SWs (Figure 3.9). In this genotype, the number of tillers reduced by 23 % in SW2, 45 % in SW3 and 88 % in SW4, comparing with SW1.

3.2.5. Grain Yield

Analysis of Variance (ANOVA) revealed that mean grain yield differ significantly ($P < 1\%$ level) with the change in sowing time over years and also due to yearly variations (Appendix 8). It revealed that 86 % of the yield variations were due to SWs. However, the genotypic differences were non-significant regarding grain yield (Appendix 8).

In SW1, average grain yield among genotypes under study varied between 4296 kg/ha and 4638 kg/ha (Appendix 9). Genotype Wafaq-2001 produced maximum grain yield of 4638 kg/ha with SD of 596 kg/ha while the lowest yield level of 4296 kg/ha (SD of 970 kg/ha) was observed in NR-55.

At SW2 the genotypic differences was non-significant (Appendix 10). Wafaq-2001 again produced highest grain yield of 4405 kg/ha at SW2 (with SD of 562 kg/ha) and NR-55 remained the lowest (4027 kg/ha with SD of 399 kg/ha).

Wafaq-2001 (3285 kg/ha with SD of 490 kg/ha) and Margalla-99 (2598 kg/ha with SD of 774 kg/ha) remained the highest and lowest yielding genotypes in SW3 respectively (Appendix 11). Data presented in Appendix 12 revealed that in SW4, grain yield levels remained below 2441 kg/ha (NR-234) with the lowest production of Chakwal-97 (1575 kg/ha).

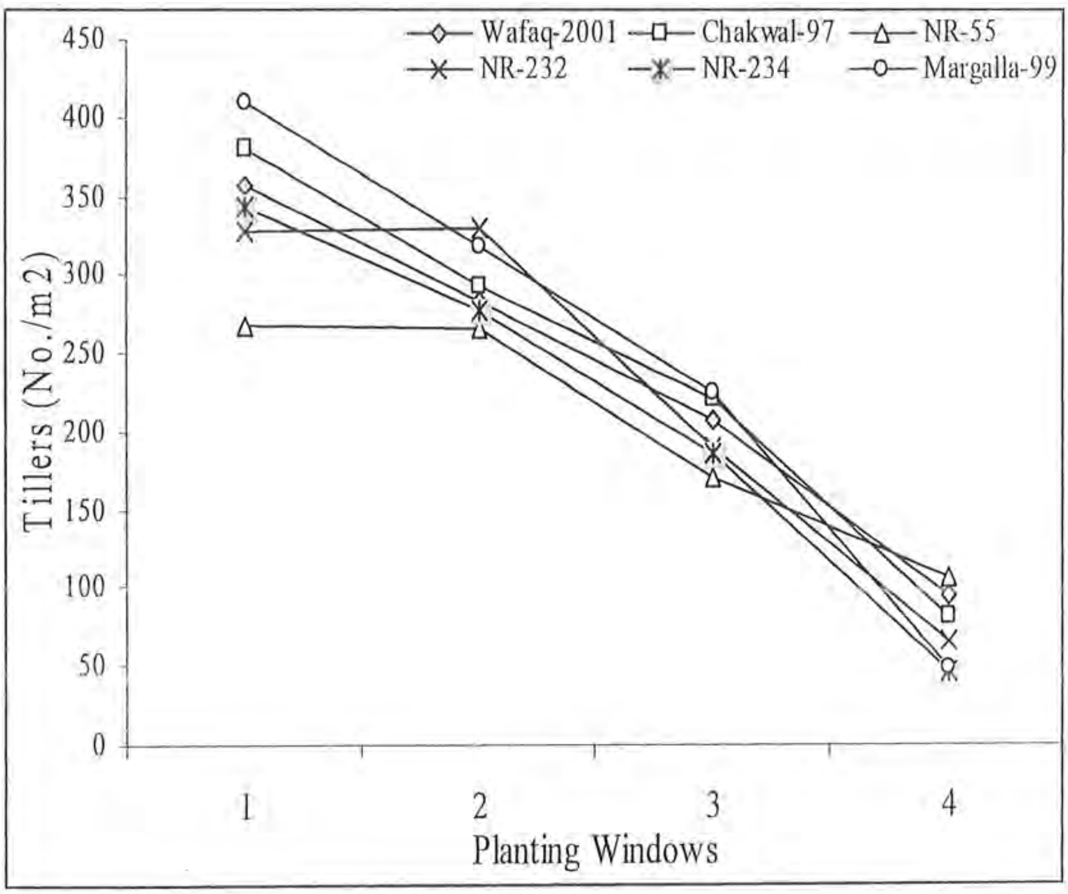

Figure 3.9 Number of tillers (per m^2) of wheat as affected by sowing windows

Grain yield reduced significantly in case of late sowing in all the genotypes (Figure 3.10). Grain weight per m^2 varied generally between 200 g/m^2 to 500 g/m^2 (Appendix 22) across genotypes and over years.

A yield reduction of 9% was observed in genotypes Margalla-99 and NR-234 with delay in sowing from SW1 to SW2 (Appendices 9-10). Margalla-99 again showed sensitivity to sowing time with 42% and 36% yield losses due to delayed sowing in SW3 when comparing with SW1 and SW2 respectively (Appendices 9-11).

Generally, genotype Chakwal-97 proved to be the most vulnerable with delay in sowing and resulted in yield losses when sown in variant SWs. Yield losses up to 66% were shown by this genotype comparing early sowing (SW1) with late sowing (SW4). 63 % yield losses were observed by delaying sowing from SW2 to SW4 and 48% from SW3 to SW4 (Figure 3.10 and Appendices 9-12).

Overall, a yield reduction of 13 - 48%, 23 - 36%, 29 - 42%, 40 - 63% and 45 - 66% was observed among these genotypes in SW3 and SW4 respectively in comparison to SW1 (Appendices 9-12). Quantification of this yield reduction showed a reduction of about 60 kg/ha/day across the genotypes under study with delay in sowing from SW1 to SW4 for this area.

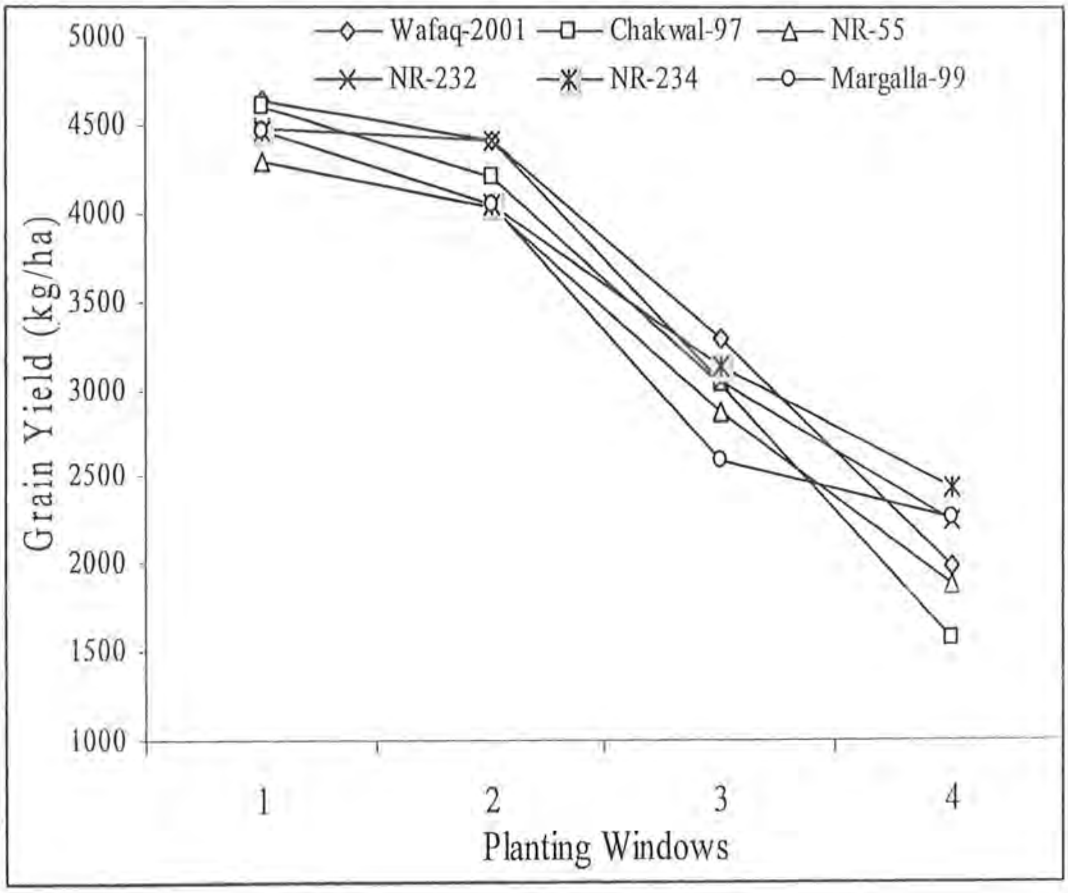

Figure 3.10 Wheat grain yield (kg/ha) as affected by sowing windows

3.3 RELATION OF CROP GROWTH PARAMETERS WITH YIELD

The direct and indirect contribution of various growth and development parameters on yield was studied for 6 genotypes sown in four Sowing Windows during 2001-2005 wheat growing seasons. The values of standardized regression coefficients in table 3.6 indicated that among the parameters biomass, number of spikelets per spike, and 1000 grain weight were the most important parameters affecting yield. The values of these parameters were statistically significant and positive. The greater the biomass the greater would be the yield and similar would be true for number of spikelets and 1000 grain weight. Days to anthesis, maturity days and number of tillers (*per* m^2) also had positive relationship with yield. Other variables like plant height (*cm*) and spike length (*cm*) had negative values of regression coefficient.

Diagramatic representation in Figure 3.11 indicated the values of correlation coefficients showing the relationship of various growth and development parameters and their direct and indirect contribution towards yield of 6 genotypes sown in 4 SWs during 2001-2005 wheat growing seasons. Anthesis (*Days after Sowing*) produced direct positive effect and indirect effects via plant height (*cm*), number of spikelets (*per spike*), number of tillers (*per* m^2), biomass (*kg per ha*) and 1000 grain weight (*g*) but these effects were nullified through negative indirect effects via maturity (*Days after Sowing*) and spike length (*cm*) resulting in the overall negative contribution of anthesis (*Days after Sowing*) towards yield (Figure 3.11)

Table 3.6 Regression summary showing the relationship between yield and other parameters studied for 6 genotypes sown in 4 sowing windows during 2001-2005 wheat growing seasons.

	Anthesis *(Days after Sowing)*	Maturity *(Days after Sowing)*	Plant Height (cm)	Spike Length (cm)	No. of Spikelets (per spike)	No. of Tillers (per m^2)	Biomass (kg/ha)	1000 Grain Weight (gm)	Standardized Regression coefficients for Yield⇑
Anthesis *(Days after Sowing)*	1.0000	-0.7982	0.0161	-0.1040	0.0049	0.2261	0.0447	0.1877	**0.036560**
Maturity *(Days after Sowing)*		1.0000	-0.1402	0.2337	-0.2203	-0.1377	-0.1055	-0.2033	**0.047256**
Plant Height (cm)			1.0000	-0.0200	0.1009	-0.2476	-0.4563	-0.2146	**-0.087769**
Spike Length (cm)				1.0000	-0.7966	0.2137	-0.3027	0.1072	**-0.073059***
No. of Spikelets (per spike)					1.0000	-0.3097	0.2710	-0.1095	**0.115865*****
No. of Tillers (per m^2)						1.0000	-0.5692	0.1684	**0.010859**
Biomass (kg/ha)							1.0000	-0.0805	**0.876933*****
1000 Grain Weight (gm)								1.0000	**0.071379*****

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level, * Significant at $P < 10\%$ level
⇑Values in bold font style showed direct effects of these parameters on yield.

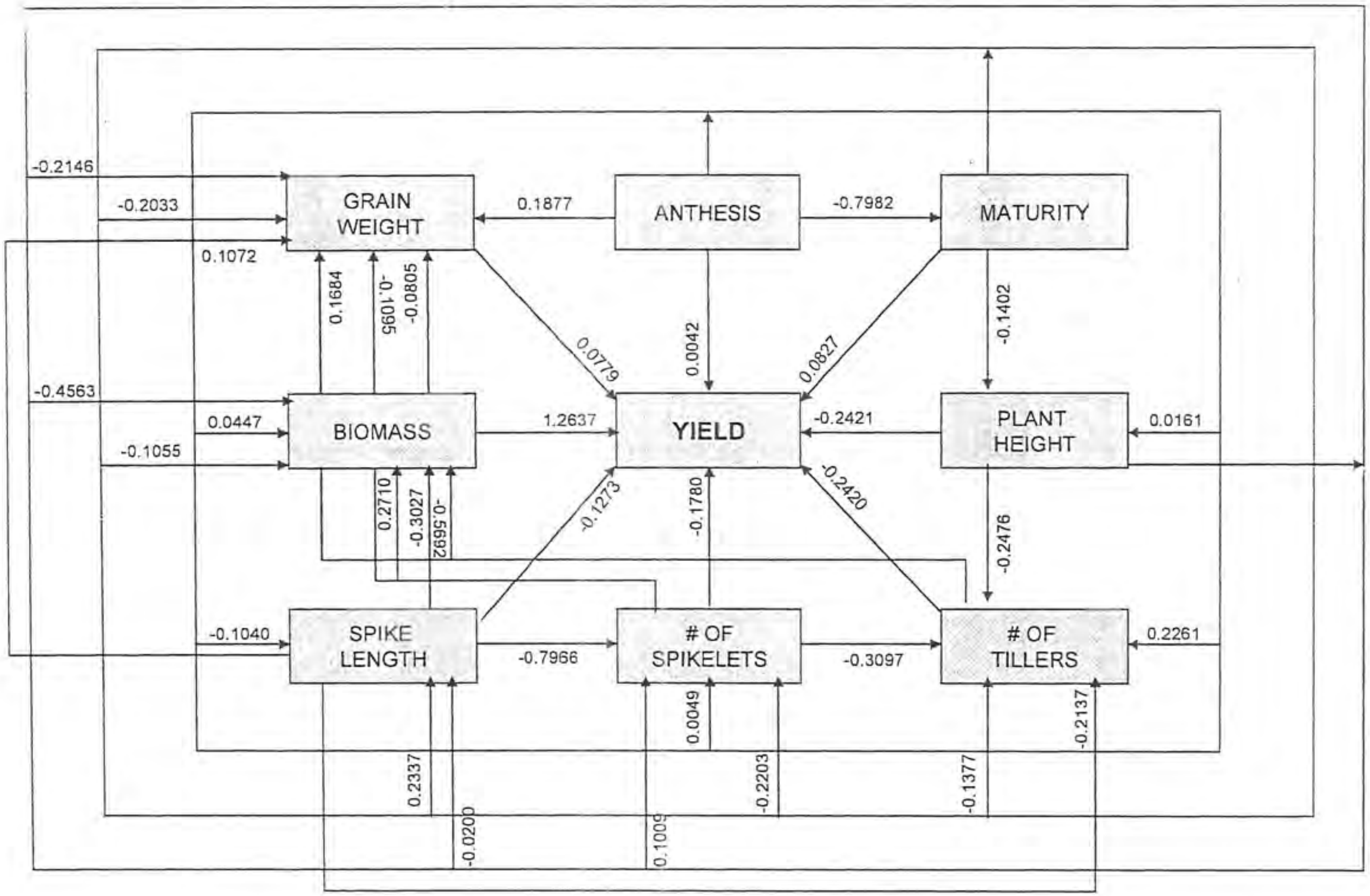

Figure 3.11 Diagramatic representation of correlation coefficients showing the relationship of various parameters and their direct and indirect contribution towards yield studied for 6 genotypes sown in 4 sowing windows during 2001-2005 wheat growing seasons.

Days to maturity (*from sowing*) produced direct positive effect and indirect positive effect through spike length (*cm*) but the overall contribution of maturity days was negative through negative indirect effects via plant height (*cm*), number of spikelets (*per spike*), number of tillers (*per m^2*), biomass (*kg per ha*) and 1000 grain weight (*g*) (Table 3.6 & Figure 3.11).

Plant height (*cm*) exhibited negative direct and overall contribution towards yield through other parameters like spike length (*cm*), number of tillers (*per m^2*), biomass (*kg per ha*) and 1000 grain weight (*g*). However, plant height (*cm*) contributed positively through number of spikelets (*per spike*) (Table 3.6 & Figure 3.11).

Spike length (*cm*) showed negative contribution directly and indirectly through number of spikelets (*per spike*) and biomass (*kg per ha*). In spite of positive indirect contributions of number of tillers (*per m^2*) and 1000 grain weight (*g*), overall spike length (cm) contributed negatively ($P < 10\%$ level) towards yield (Figure 3.11 & Table 3.6).

Number of spikelets (*per spike*) showed direct positive contribution ($P < 1\%$ level) towards yield and indirect positive contribution through biomass (*kg per ha*). However, it has negative indirect contribution through number of tillers (*per m^2*) and 1000 grain weight (*g*) (Table 3.6 & Figure 3.11).

Number of tillers (*per m^2*) produced positive indirect contribution through 1000 grain weight (*g*) but the direct negative contribution and negative indirect contribution through biomass (*kg per ha*) made the overall negative contribution of this parameter towards yield (Figure 3.11 & Table 3.6) regarding genotypes under study in this area.

Biomass (*kg per ha*) production indicated positive contribution ($P < 1\%$ level) towards yield. However, negative indirect effect through 1000 grain weight (*g*) could not nullify the overall positive effect. It is worth to mention that in the analysis it is established as a fact that 1000 grain weight (*g*) produced positive direct contribution ($P < 1\%$ level) towards yield (Figure 3.11 & Table 3.6).

3.4 GENOTYPE x ENVIRONMENT x MANAGEMENT (G x E x M) INTERACTION

3.4.1 ANALYSIS OF VARIANCE

Analysis of Variance was carried out to determine the Genotype (G) x Environment (Years) (E) x Management (sowing windows) (M) effect on grain yield, plant height, spike length, spikelets per spike, tillers per m^2, biomass and 1000 grain weight (Appendices 23-29). Analysis also included all possible interactions among these factors on yield, yield components and other agronomic traits. Analysis was done using sowing windows (M), Genotypes (G), and their interaction against replication, and remaining sources of variations from Years (E) and all possible interactions were tested against the residual.

The significant components of G x E x M interaction for yield were M, followed by M x E interaction, E, G x E x M interaction, and G x E interaction (Appendix 23).

The significant components for G x E x M interaction for plant height were M, followed by M x E interaction, G x E x M interaction, and E (Appendix 24).

Regarding spike length, G x E, M x E interaction and G x E x M interaction were the significantly contributing components of G x E x M interaction in descending order (Appendix 25).

In case of spikelets per spike, M x E interaction, M, and G x E x M interaction was the significant contributor among the components of G x E x M interaction in descending order (Appendix 26).

Regarding tillers per m^2, the significant components of G x E x M interaction were M followed by M x E interaction and G x E x M interaction (Appendix 27).

Among the components of G x E x M interaction studied for biomass (*kg /ha*) at maturity, M played a significant role. Among others, M x E interaction contributed significantly followed by the effects of E and G x E x M interaction regarding biomass at maturity (Appendix 28).

Regarding 1000 grain weight, M played the significant contribution. Analysis revealed that among other components of G x E x M interaction, the effects of M x E interaction and E were significant towards 1000 grain weight (Appendix 29).

Considering yield across all years G x E sum of squares explained only 5% of the total, with G accounted for 1% and E 8%. M played a significant role in grain yield with the contribution of 57% to the total sum of squares. The M contribution towards total sum of squares was 67%, 62%, 66% and 35% for plant height, tillers per m^2, biomass and 1000 grain weight respectively. M x E interaction contributed 30% for spikelets per spike and G x E interaction contributed 18% for spike length towards total sum of squares (Appendices 23-29).

3.4.2 GENOTYPIC PERFORMANCE

Yields of genotypes averaged across sowing windows in a year varied from 2.4 to 5.0 t/ha (Table 3.7). Genotypic performance over six years revealed a varying trend. During wheat growing season 2001-02 Wafaq-2001 performed better, NR-232 ranked highest during 2002-03 and 2003-04, Chakwal-97 and Wafaq-2001 performed better

Table 3.7 Mean yield (kg/ha) of wheat listed as Genotype x Environment two-way data format.

Environments (Years)	Genotypes														
	Wafaq-2001		Chakwal-97		NR-55		NR-232		NR-234		Margalla-99				
	Y[a]	% D[b]	Y	% D	Y	% D	Y	% D	Y	% D	Y	% D	Mean	SD[c]	C[d]
2001-02	3742	**15**	3404	6	2373	*-34*	2909	*-10*	3350	5	3352	**5**	3188	479	384
2002-03	2795	*-9*	2832	-8	3050	0	3460	**12**	3241	**6**	2927	-4	3051	258	206
2003-04	3691	4	3098	*-15*	3773	6	3954	10	3706	4	3075	-15	3550	371	297
2004-05	4092	3	4068	3	3879	-2	3841	-3	3802	-4	4029	2	3952	126	101
2005-06	4340	7	5026	**20**	4665	13	3931	-3	3663	-10	2648	*-53*	4046	842	674
2006-07	4083	8	4591	**18**	3927	4	3927	4	3166	*-19*	2889	-30	3764	626	501
Mean	3791		3837		3611		3670		3488		3153		3592		
SD	544		869		795		416		269		488				
C	436		696		636		333		215		390				

[a] Yield in kg per ha

[b] Percent difference between individual genotype mean across all sowing windows and mean of all genotypes in a year.

[c] Standard Deviation

[d] Confidence interval for the mean at $P < 5\%$ level

Values with special font format indicate years when a genotype performed best (bold) and worst (italic) respectively.

in 2004-05 and Chakwal-97 found superior during 2005-07 growing seasons (Table 3.7).

The genotype, Chakwal-97 produced a mean yield of 3837 kg/ha averaged across SWs and over the years. SD was 869 kg/ha with a confidence interval of 696 kg/ha at 5 % probability level (Table 3.7). Among the genotypes under study, Margalla-99 was the lowest yielding cultivar (3153 kg/ha) with SD of 488 kg/ha and a confidence interval of 390 kg/ha at 5 % probability level (Table 3.7).

All the genotypes performed better during 2005-06, with mean yield of 4046 kg/ha averaged across SWs and genotypes, as compared with other years. However, these genotypes produced an average yield of 3051 kg/ha having SD of 258 kg/ha with a confidence interval of 206 kg/ha during 2002-03 wheat growing season and it was the lowest yielding year.

Biomass at maturity averaged across sowing windows in a year varied from 9.3 to 15.7 t/ha (Table 3.8). Genotypic performance over six years revealed Margalla-99 accumulated maximum biomass during 2001-02 growing season while NR-234 performed better among the genotypes during 2002-03. NR-55, NR-232 and NR-234 performed better during 2003-04 while Wafaq-2001 accumulated highest biomass in 2004-05 and 2006-07 seasons. Chakwal-97 found superior during 2005-06 growing season whereas, during the same year Margalla-99 showed 36 % reduction in total above ground biomass at maturity (Table 3.8).

Table 3.8 Mean biomass (kg/ha) of wheat listed as Genotype x Environment two-way data format⇮.

Environments (Years)	Genotypes													
	Wafaq-2001		Chakwal-97		NR-55		NR-232		NR-234		Margalla-99				
	B[a]	% D[b]	B	% D	B	% D	B	% D	B	% D	B	% D	Mean	SD[c]	C[d]
2001-02	10710	4	10374	0	8417	*-23*	10042	-3	11176	**8**	11243	**8**	10327	1043	835
2002-03	9333	*-8*	9317	*-8*	10098	0	10500	4	10958	**8**	10383	3	10098	660	528
2003-04	10986	*-8*	11018	*-8*	12555	5	12495	5	12527	5	11727	-1	11884	751	601
2004-05	12829	5	12489	2	11783	-3	11732	*-4*	11949	-2	12317	1	12183	435	348
2005-06	14617	8	15717	14	15123	**11**	13861	3	11655	-16	9900	*-36*	13479	2249	1799
2006-07	13417	**11**	12457	4	13310	10	13310	**10**	9550	*-25*	9499	-26	11924	1891	1513
Mean	11982		11895		11881		11990		11302		10845		11649		
SD	1967		2236		2375		1522		1024		1097				
C	1574		1789		1900		1218		820		878				

[a] Biomass in kg per ha

[b] Percent difference between individual genotype mean across all sowing windows and mean of all genotypes in a year.

[c] Standard Deviation

[d] Confidence interval for the mean at $P < 5\%$ level

⇮Values with special font format indicate years when a genotype performed best (bold) and worst (italic) respectively.

Regarding biomass production, Margalla-99 showed less mean biomass production averaged across SWs and over the years. Having SD of 1097 kg/ha Margalla-99 produced 10845 kg/ha biomass with a confidence interval of 878 kg/ha at $P < 5$ % probability level (Table 3.8). Among the genotypes under study, Wafaq-2001 (11982 Kg/ha) and NR-232 (11990 kg/ha) showed maximum biomass production over the years (Table 3.8).

Genotypic performance regarding biomass production was found again better during 2005-06, with mean total above ground biomass of 13479 kg/ha averaged across SWs and genotypes. With SD of 2249 kg/ha, these genotypes produced highest average biomass having a confidence interval of 1799 kg/ha. Similar to yield (Table 3.7), genotypes could not perform well regarding biomass production at maturity during 2002-03 growing season (Table 3.8).

Plant height attained by the genotypes averaged across sowing windows in a year varied from 89 cm to 113 cm (Table 3.9). Genotypic performance varied with yearly variations. Among the genotypes maximum height was gained by NR-234 during 2001-02, Margalla-99 during 2002-03, NR-232 during 2003-04, Wafaq-2001 during 2004-05, Chakwal-97 during 2005-06 and Wafaq-2001 during 2006-07. Margalla-99 gained less height and showed 14 % and 11 % reduction in plant height during 2005-06 and 2006-07 growing seasons respectively, (Table 3.9) from the mean height gained by all genotypes during the respective years.

Average plant height of these genotypes remained below 100 cm. Wafaq-2001, NR-55 and NR-232 gained mean plant height of 99 cm with SD of 8 cm, 9 cm and 7 cm

Table 3.9 Mean plant height (cm) of wheat listed as Genotype x Environment two-way data format♕.

Environments (Years)	Genotypes														
	Wafaq-2001		Chakwal-97		NR-55		NR-232		NR-234		Margalla-99				
	PH[a]	% D[b]	PH	% D	PH	% D	PH	% D	PH	% D	PH	% D	Mean	SD[c]	C[d]
2001-02	89	*-3*	92	-1	89	*-4*	93	1	96	**4**	95	**3**	92	3	2
2002-03	92	0	89	-3	92	0	92	0	92	0	94	2	92	1	1
2003-04	101	2	94	*-5*	101	2	102	3	97	-2	99	0	99	3	2
2004-05	100	3	98	1	97	-1	96	*-2*	96	-2	98	1	98	2	1
2005-06	110	4	113	**7**	111	6	108	2	97	*-9*	92	*-14*	105	9	7
2006-07	105	**6**	94	*-5*	105	**7**	105	**7**	91	-8	89	-11	98	8	6
Mean	99		97		99		99		95		94		97		
SD	8		9		9		7		3		4				
C	6		7		7		5		2		3				

[a] Plant Height in cm
[b] Percent difference between individual genotype mean across all sowing windows and mean of all genotypes in a year.
[c] Standard Deviation
[d] Confidence interval for the mean at $P < 5\%$ level
♕Values with special font format indicate years when a genotype performed best (bold) and worst (italic) respectively.

respectively (Table 3.9). The confidence interval of plant height for these genotypes varied between 5 cm and 7 cm ($P < 5\%$ level).

Similar to yield and biomass production, these genotypes gained mean maximum plant height of 105 cm during 2005-06 and the mean minimum plant height was observed during 2002-03 wheat growing seasons (Table 3.9).

Tiller production among genotypes averaged across sowing windows in a year varied from 166 per m^2 to 370 per m^2 (Table 3.10). Genotypic performance over six years revealed a varying trend. During wheat growing season 2001-02 Chakwal-97 performed better, Margalla-99 produced higher number of tillers (per m^2) across SWs during 2002-03 and 2003-04, Wafaq-2001 produced higher number of tillers (per m^2) in 2004-05 and also found superior during 2005-06 growing seasons (Table 3.10).

Overall, Wafaq-2001 produced maximum number of tillers with a mean of 279 per m^2, having SD of 53 per m^2 with a confidence interval of 43 per m^2 at $P < 5\%$ level (Table 3.10). Among the genotypes under study, NR-234 was the lowest tillers producing genotype with mean tiller production of 239 per m^2 across SWs and over the years. SD of 41 tillers per m^2 was observed for NR-234 and a confidence interval of 33 tillers per m^2 was found for this mean ($P < 5$ % level) (Table 3.10).

Genotypic performance regarding production of tillers (numbers per m^2) was better during 2005-06, with 314 mean tillers per m^2 produced across SWs and genotypes (Table 3.10). SD for this mean was 55 tillers per m^2 having a confidence interval of 44 tillers per m^2 around this mean of 314 tillers per m^2 at $P < 5\%$ level. Like other

Table 3.10 Mean tillers (# per m^2) of wheat listed as Genotype x Environment two-way data format.

Environments (Years)	Genotypes														
	Wafaq-2001		Chakwal-97		NR-55		NR-232		NR-234		Margalla-99				
	T[a]	% D[b]	T	% D	T	% D	T	% D	T	% D	T	% D	Mean	SD[c]	C[d]
2001-02	255	3	270	**9**	202	*-22*	229	*-8*	263	**6**	263	6	247	26	21
2002-03	211	-4	213	-3	220	0	226	3	213	-3	235	7	220	10	8
2003-04	256	*-6*	255	*-6*	287	6	268	-1	266	-2	294	**8**	271	16	13
2004-05	289	5	283	3	267	-3	265	-3	266	-3	272	0	274	10	8
2005-06	370	**15**	346	**9**	350	10	329	4	261	-20	231	*-36*	314	55	44
2006-07	290	10	269	3	316	**17**	316	**17**	166	*-58*	214	-22	262	60	48
Mean	279		272		274		272		239		252		265		
SD	53		43		56		43		41		30				
C	43		35		45		34		33		24				

[a] Tillers in # per m^2

[b] Percent difference between individual genotype mean across all sowing windows and mean of all genotypes in a year.

[c] Standard Deviation

[d] Confidence interval for the mean at $P < 5\%$ level

Values with special font format indicate years when a genotype performed best (bold) and worst (italic) respectively.

crop parameters, minimum number of tillers were produced during 2002-03. Average number of tillers produced across SWs and genotypes during 2002-03 growing season was 220 per m^2 having SD of 10 tillers per m^2 and a confidence of only 8 tillers per m^2 at $P < 5\%$ level (Table 3.10).

1000 grain weight averaged across sowing windows in a year varied from 31 g to 43 g (Table 3.11). During wheat growing season 2001-02 NR-55 gained maximum average 1000 grain weight (40 g) across SWs in that year. NR-232 ranked highest during 2002-03 (40 g), NR-234 achieved maximum 1000 grain weight (36 g) during 2003-04, while NR-232 gained maximum 1000 grain weight (43 g) in 2005-06 (Table 3.11).

Overall, NR-232 produced a mean 1000 grain weight of 39 g averaged across SWs and over the years. SD was 3 g with a confidence interval of 2 g at $P < 5\%$ level (Table 3.11). Among the genotypes under study, Margalla-99 produced grains with the lowest 1000 grain weight (36 g) with SD of 3 g and a confidence interval of 2 g at $P < 5\%$ level (Table 3.11).

Genotypic performance was found better during 2002-03, with mean 1000 grain weight of 39 g averaged across SWs and genotypes. However, these genotypes during 2003-04 produced grains with 35 g weight of 1000 grains which was the lowest 1000 grain weight among years under study (Table 3.11).

Spike length did not exhibit much variation and the average spike length among genotypes across sowing windows in a year varied from 9 cm to 11 cm (Table 3.12). Mean maximum spike length of 11 cm and minimum of 10 cm was calculated across

Table 3.11 Mean thousand grain weight (g) of wheat listed as Genotype x Environment two-way data format‡.

Environments (Years)	Genotypes														
	Wafaq-2001		Chakwal-97		NR-55		NR-232		NR-234		Margalla-99				
	TGW[a]	% D[b]	TGW	% D	TGW	% D	TGW	% D	TGW	% D	TGW	% D	Mean	SD[c]	C[d]
2001-02	38	*-1*	36	*-7*	40	**4**	39	3	38	0	38	0	38	1	1
2002-03	38	*-1*	39	1	39	0	40	2	39	1	38	-3	39	1	1
2003-04	35	0	35	-1	36	1	36	2	36	3	33	-6	35	1	1
2004-05	38	1	38	0	38	-1	38	0	38	1	38	-1	38	0	0
2005-06	42	**8**	38	0	40	**4**	43	**10**	37	*-4*	31	*-25*	38	4	3
2006-07	39	3	38	**3**	36	*-5*	36	*-5*	39	**4**	37	-1	37	1	1
Mean	38		38		38		39		38		36		38		
SD	2		2		2		3		1		3				
C	2		1		2		2		1		2				

[a] Thousand Grain Weight in g
[b] Percent difference between individual genotype mean across all sowing windows and mean of all genotypes in a year.
[c] Standard Deviation
[d] Confidence interval for the mean at $P < 5\%$ level
‡Values with special font format indicate years when a genotype performed best (bold) and worst (italic) respectively.

Table 3.12 Mean spike length (cm) of wheat listed as Genotype x Environment two-way data format⇑.

Environments (Years)	Genotypes														
	Wafaq-2001		Chakwal-97		NR-55		NR-232		NR-234		Margalla-99				
	SL[a]	% D[b]	SL	% D	SL	% D	SL	% D	SL	% D	SL	% D	Mean	SD[c]	C[d]
2001-02	9	*-11*	11	6	10	0	10	1	11	2	10	1	10	1	0
2002-03	11	1	10	*-3*	10	0	10	*-3*	11	**3**	11	**2**	10	0	0
2003-04	10	-7	10	*-3*	11	1	11	**8**	11	1	10	-2	10	1	0
2004-05	11	1	11	1	11	-1	11	-1	11	*-1*	11	0	11	0	0
2005-06	11	4	10	*-3*	11	-1	10	-2	11	0	11	**2**	11	0	0
2006-07	11	3	11	4	11	*-2*	11	-2	11	*-1*	10	*-3*	11	0	0
Mean	10		11		11		11		11		11		11		
SD	1		0		0		0		0		0				
C	1		0		0		0		0		0				

[a] Spike Length in cm

[b] Percent difference between individual genotype mean across all sowing windows and mean of all genotypes in a year.

[c] Standard Deviation

[d] Confidence interval for the mean at $P < 5\%$ level

⇑Values with special font format indicate years when a genotype performed best (bold) and worst (italic) respectively.

SWs and over the years. Similarly, spike length varied between 10 cm and 11 cm averaged across SWs and genotypes (Table 3.12).

Genotypic performance over six years revealed that spikelets number per spike varied from 18 to 21 (Table 3.13). Overall, 19 - 20 spikelets were observed per spike when averaged across SWs and years. Similar range was also observed across SWs and genotypes revealing that genotypic differences were not observed regarding number of spikelets per spike over the years.

Table 3.13 Mean spikelets (# per spike) of wheat listed as Genotype x Environment two-way data format⌂.

Environments (Years)	Genotypes														
	Wafaq-2001		Chakwal-97		NR-55		NR-232		NR-234		Margalla-99				
	SN[a]	% D[b]	SN	% D	SN	% D	SN	% D	SN	% D	SN	% D	Mean	SD[c]	C[d]
2001-02	18	*-7*	21	**7**	19	*-2*	20	0	20	**1**	20	0	20	1	1
2002-03	19	2	18	-4	19	0	19	*-2*	19	0	20	**3**	19	0	0
2003-04	19	-4	19	1	20	**1**	20	**1**	19	0	19	0	19	0	0
2004-05	20	1	20	1	20	-1	20	-1	20	0	20	0	20	0	0
2005-06	21	**5**	19	*-5*	20	-1	20	-1	20	0	20	1	20	1	1
2006-07	20	2	21	**7**	19	*-2*	19	*-2*	19	*-2*	19	*-4*	20	1	1
Mean	20		20		19		19		20		20		20		
SD	1		1		0		0		0		0				
C	1		1		0		0		0		0				

[a] Spikelets in # per spike

[b] Percent difference between individual genotype mean across all sowing windows and mean of all genotypes in a year.

[c] Standard Deviation

[d] Confidence interval for the mean at $P < 5\%$ level

⌂Values with special font format indicate years when a genotype performed best (bold) and worst (italic) respectively.

3.4.3 Relationship of Wheat Genotypes with Environmental Variables, Years and Sowing Windows for Yield

Results obtained after projecting the variables in a biplot based on Principal Component and Classification Analysis (PCCA) for yield (Figure 3.12) and the data presented in appendix 30 revealed that overall the best year was 2005-06. Other variables relating to crop (yield components and agronomic traits) and environment (total precipitation, mean monthly temperature, bright sunshine duration and solar radiation for the months of October, November, December, January, February, March, April and May) were also seen on the projection plane to be either positively or negatively associated with yield (Table 3.14 and Figure 3.12).

Principal Component (PC) 1 explains 67% of the total variance and PC2 explains 28% variance. Eigenvalue (*variance explained by the correlation between the respective canonical variates or underlying latent variables*) for PC1 and PC2 found to be 4.02 and 1.70 respectively. Cumulatively these two factors explained 95% of the total variance.

Among the variables contributing in PC1, the most significant contributions made by genotypic traits included days taken to anthesis and maturity; environmental factors included solar radiations during March, average temperature during April, precipitation during December, sunshine duration during January, February, December; and management included sowing in SW 1.

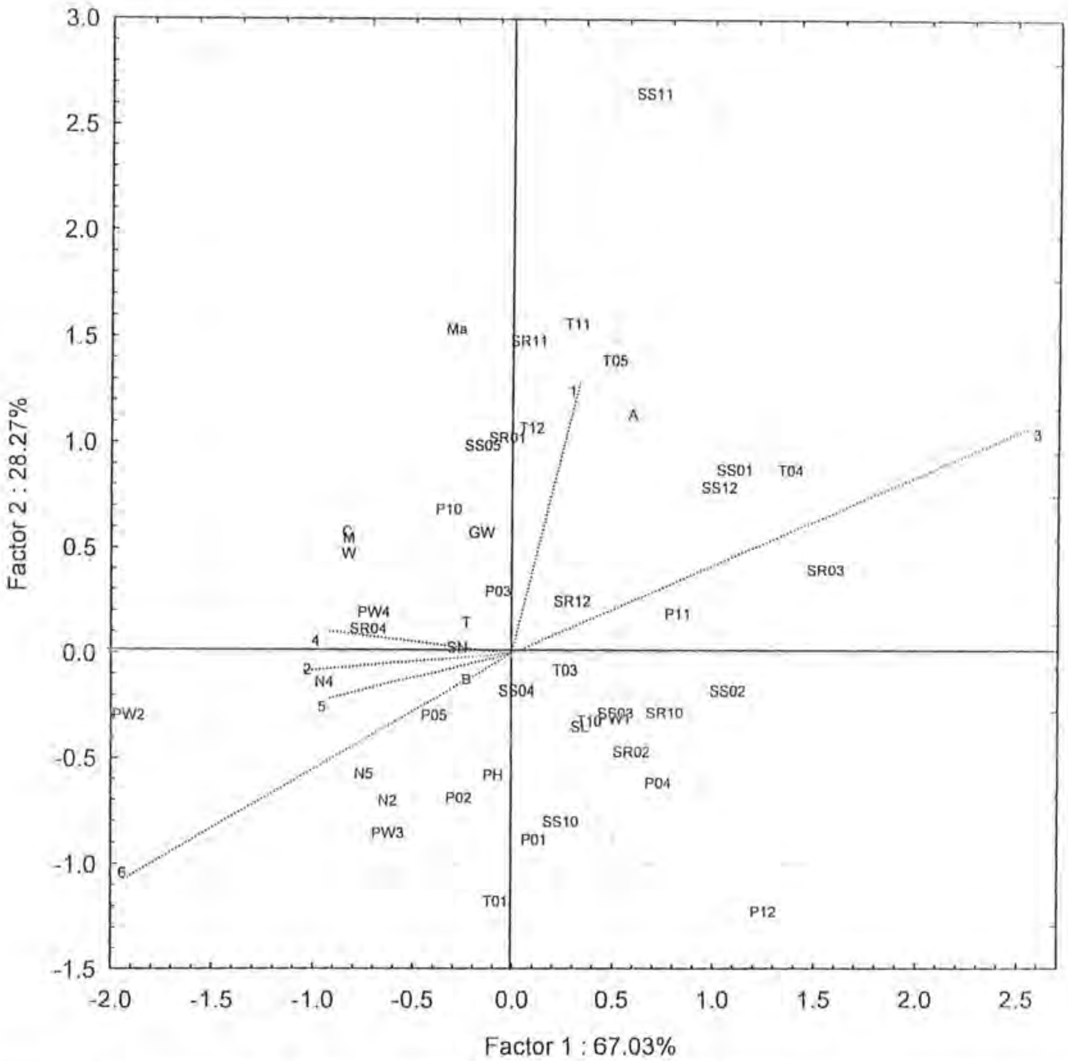

Figure 3.12 Projection of the variables on the (1x2) factor plane, a biplot based on PCCA result for 6 wheat cultivars showing the relationship with environmental variables, years and sowing windows for yield. Environmental variables used in the analysis included total precipitation (P) in mm, average temperature (T) in ^{o}C, total sunshine duration in hours (SS) and solar radiation (SR) in $MJ/m^2/day$ and abbreviated with the # as 10, 11, 12, 01, 02, 03, 04 and 05 for the months of October-May; agronomic traits included days taken to Anthesis (A), Maturity (Ma), Plant Height (PH), Tillers per m^2 (T), Spike Length (SL), Spikelets Number per spike (SN) and 1000 Grain Weight (GW). Genotypes were abbreviated as W= Wafaq-2001, C = Chakwal-97, N5 = NR-55, N2 = NR-232, N4 = NR-234 and M = Margalla-99.

Days taken to anthesis and maturity (genotypic traits); sunshine duration, average temperature and solar radiations during November (environmental factors) were important explaining variables for PC2.

To further elucidate the results, the correlation of crop growth and development variables with yield was performed. Correlation between percent difference of variables with percent difference of yield across sowing windows and years was also performed (Table 3.9). It depicts that the yield of these genotypes was highly interacted with biomass followed by tillers per m^2 and plant height. Other variables showed a varying interaction with yield of various genotypes.

Table 3.14 Correlation of crop growth and development variables with yield (bold) and correlation between percent difference of these variables with percent difference of yield (italic) across sowing windows (SW1, 2, 3 and 4) and years (2001-2007)

Variables	Genotypes											
	Wafaq-2001		Chakwal-97		NR-55		NR-232		NR-234		Margalla-99	
	Cvy[a]	Cdvy[b]	Cvy	Cdvy	Cvy	Cdvy	Cvy	Cdvy	Cvy	Cdvy	Cvy	Cdvy
Plant Height (cm)	**0.74**	*-0.07*	**0.78**	*0.56*	**0.94**	*0.82*	**0.73**	*0.23*	**0.85**	*0.87*	**0.64**	*0.96*
Spike Length (cm)	**0.32**	*-0.44*	**0.30**	*0.36*	**0.77**	*-0.37*	**0.36**	*0.24*	**-0.15**	*0.80*	**0.03**	*0.09*
Spikelets (per spike)	**0.52**	*-0.42*	**0.26**	*0.18*	**0.77**	*0.32*	**0.27**	*-0.12*	**0.62**	*0.80*	**0.18**	*0.17*
Tillers (#/m^2)	**0.88**	*0.48*	**0.86**	*0.83*	**0.95**	*0.91*	**0.74**	*0.39*	**0.81**	*0.91*	**0.57**	*0.90*
Biomass (kg per ha)	**0.92**	*0.63*	**0.93**	*0.91*	**0.98**	*0.97*	**0.86**	*0.64*	**0.87**	*0.99*	**0.84**	*0.97*
1000 Grain Weight (g)	**0.40**	*0.24*	**0.36**	*0.10*	**-0.25**	*-0.34*	**-0.23**	*-0.26*	**-0.69**	*-0.01*	**0.55**	*0.84*

[a] Cvy = Correlation of variables with yield

[b] Cdvy = Correlation of percent difference of variables with percent difference of yield.

3.5 PARAMETERIZATION AND EVALUATION OF APSIM-WHEAT MODULE

3.5.1 EVALUATION OF APSIM-WHEAT MODULE

Evaluation of any simulation model against an independent data set is an essential step in model development. In the present work, APSIM-Wheat module was tested for wheat phenology, biomass production and yield with the objectives to predict the duration of growth, biomass production and yield of the wheat.

3.5.1.1 Crop Phenology and Morphology

With the generic genetic coefficients, the model was unable to track accurately the duration of crop growth. Simulated responses regarding occurrence of anthesis for Wafaq-2001 were earlier than measured values by 3 to 37 days (Table 3.15 and Appendix 31). However, for Chakwal-97 simulations were accurate for December sowing but with November sowings anthesis was delayed by 3 to 5 days compared to measured values. In October sowing, anthesis was simulated earlier by up to 3 weeks. For an advance line NR-55 occurrence of anthesis was simulated earlier by 1 to 8 days with October and November sowings but with December sowing it was delayed by 5 days. Simulated and measured means were significantly different ($P < 5\%$ level) for all sowing windows for Chakwal-97, October and November sowings for Wafaq-2001 while early and late sowings for NR-55 (Table 3.15). r^2 for these genotypes ranged from 0.04 to 0.43 for sowing windows 1, 2, 3 and 4.

The simulated and measured maturity for Wafaq-2001 was under-predicted by 13 to 32 days in sowing windows 1, 2, 3 and 4 with r^2 varied between 0.06 and 0.43 (Table 3.16 and Appendix 32). Like wise the model under-predicted the maturity for Chakwal-97 and NR-55 by 8 to 26 days and 1 to 16 days respectively. All simulated

Table 3.15 Comparison of simulated and measured values[a] regarding anthesis (*Days after Sowing*)

Sowing Windows (SW)	Measured		Simulated		Bias	*T*	Regression Equation	r^2
	Mean	SD	Mean	SD				
Anthesis (Days after Sowing)								
Wafaq-2001								
SW 1	136	3	99	3	-37	-15.5*	S=-0.44M+158.37	0.28
SW 2	126	2	114	1	-12	-7.89*	S=0.237M+84.079	0.36
SW 3	118	3	110	1	-08	-3.95*	S=-0.12M+124.39	0.18
SW 4	103	2	100	1	-03	-1.71	S=0.158M+83.789	0.16
Chakwal-97								
SW 1	137	3	113	3	-24	-15.7*	S=-0.07M+118.79	0.04
SW 2	127	3	132	2	05	2.34*	S=0.214M+103.86	0.43
SW 3	120	4	123	2	03	0.88*	S=-0.12M+136.71	0.31
SW 4	105	1	105	2	00	-1.00*	S=-0.50M+156.50	0.25
NR-55								
SW 1	136	3	128	3	-08	-5.75*	S=-0.11M+139.54	0.11
SW 2	126	2	124	2	-02	-2.32	S=0.250M+91.5	0.25
SW 3	118	2	117	2	-01	-1.49	S=-0.16M+134.68	0.16
SW 4	105	1	110	2	05	4.11*	S=0.214M+86.57	0.11

[a]Arithmetic means and standard deviation (SD), bias, t statistics, regression equations of simulated (S) and measured (M) values, and coefficient of determination (r^2) for anthesis.

* Means significantly different at $P < 5\%$ level

and measured means were significantly different ($P < 5\%$ level) for Wafaq-2001 and Chakwal-97 while for NR-55, sowings in October and early November have significantly different ($P < 5\%$ level) measured and simulated occurrence of maturity days after sowing. r^2 varied between 0.06 and 0.43 for Wafaq-2001, between 0.06 and 0.96 for Chakwal-97, and 0.36 and 0.75 for NR-55 (Table 3.16).

The model under-predicted plant height irrespective of sowing time (Table 3.17 and Appendix 33). Simulated and measured means were significantly different ($P < 5\%$ level) for all the genotypes (viz., Wafaq-2001, Chakwal-97, Margalla-99, NR-55, NR-232 and NR-234).

3.5.1.2 Biomass

APSIM-Wheat module using the generic cultivar coefficients under-predicted biomass for Chakwal-97 and Wafaq-2001 over all the sowing windows while for NR-55, NR-232, NR-234 and Margalla-99 it under-predicted biomass with October and November sowing dates and at the same time over-predicted for December sowing dates. This output exhibited a significant difference ($P < 5\%$ level) among all the simulated and observed means for Chakwal-97, NR-232, NR-234 and Margalla-99 with all the sowing windows whereas for Wafaq-2001 and NR-55 mean biomass for December sowings was non-significantly different ($P < 5\%$ level) only, all other means were significantly different (Table 3.18 and Appendix 34).

Table 3.16 Comparison of simulated and measured values⁂ regarding crop maturity (*Days after Sowing*).

Sowing Windows (SW)	Measured		Simulated		Bias	*t*	Regression Equation	r^2
	Mean	SD	Mean	SD				
Maturity (Days after Sowing)								
Wafaq-2001								
SW 1	179	3	147	2	-32	-17.6*	S=-0.21M+184.29	0.43
SW 2	168	1	148	2	-20	-24.2*	S=-0.12M+166.42	0.06
SW 3	153	3	140	2	-13	-8.57*	S=-0.07M+149.93	0.04
SW 4	143	2	129	2	-14	-9.38*	S=0.158M+105.47	0.16
Chakwal-97								
SW 1	179	2	153	2	-26	-20.0*	S=-0.12M+172.62	0.06
SW 2	168	2	154	2	-14	-11.0*	S=0.346M+94.962	0.52
SW 3	153	1	145	2	-08	-08.8*	S=-0.64M+242.57	0.96
SW 4	143	2	133	2	-10	-07.8*	S=-0.38M+185.75	0.75
NR-55								
SW 1	179	2	163	2	-16	-11.93*	S=0.38M+94.75	0.75
SW 2	168	1	162	1	-06	-06.32*	S=0.43M+89.14	0.43
SW 3	153	2	151	1	-02	-02.13	S=0.24M+113.67	0.36
SW 4	143	1	142	2	-01	-02.21	S=-0.43M+202.43	0.43

⁂ Arithmetic means and standard deviation (SD), bias, t statistics, regression equations of simulated (S) and measured (M) values, and coefficient of determination (r^2) for maturity.

* Means significantly different at $P < 5\%$ level

Table 3.17 Comparison of simulated and measured values⇑ regarding plant height (*mm*).

Sowing Windows (SW)	Measured		Simulated		Bias	*t*	Regression Equation	r^2
	Mean	SD	Mean	SD				
Plant height (mm)								
Wafaq-2001								
SW 1	1084	14	165	11	-919	-89.349*	S=-0.588M+1181.1	0.23
SW 2	1020	36	205	23	-815	-33.454*	S=-1.495M+1325.8	0.90
SW 3	861	37	191	32	-670	-23.849*	S=-1.111M+1073.7	0.92
SW 4	682	34	199	27	-482	-23.273*	S= 0.497M+583.05	0.31
Chakwal-97								
SW 1	1093	20	214	18	-878	-56.944*	S=-0.886M+1282.3	0.62
SW 2	1007	06	272	30	-735	-41.229*	S=-0.187M+1058	0.90
SW 3	869	41	243	33	-626	-20.605*	S=-1.034M+1120.7	0.66
SW 4	669	125	244	31	-425	-07.862*	S= 1.397M+327.93	0.24
NR-55								
SW 1	1082	13	299	21	-797	-53.986*	S=-0.455M+1218.2	0.51
SW 2	940	44	335	25	-584	-20.634*	S= 1.468M+448.6	0.70
SW 3	739	52	308	30	-401	-12.453*	S= 1.481M+283.05	0.73
SW 4	664	41	277	37	-341	-12.264*	S= 0.410M+550.56	0.14

⇑Arithmetic means and standard deviation (SD), bias, t statistics, regression equations of simulated (S) and measured (M) values, and coefficient of determination (r^2) for plant height.

* Means significantly different at $P < 5\%$ level

Table 3.17 Continued....

Sowing Windows (SW)	Measured		Simulated		Bias	*t*	Regression Equation	r^2
	Mean	SD	Mean	SD				
Plant height (mm)								
NR-232								
SW 1	1150	55	238	17	-912	-37.000*	S=-0.441M+1254.8	0.04
SW 2	1086	23	272	30	-814	-41.153*	S=-0.301M+1167.9	0.32
SW 3	921	11	243	33	-678	-35.131*	S= 0.103M+896.12	0.18
SW 4	563	23	244	31	-319	-14.284*	S=-0.565M+700.98	0.58
NR-234								
SW 1	1084	03	339	13	-740	-83.606*	S=-0.292M+1183.5	0.26
SW 2	1019	18	274	43	-726	-22.576*	S= 0.431M+900.83	0.13
SW 3	876	60	213	15	-663	-15.185*	S= 3.899M+44.143	0.31
SW 4	634	14	207	24	-427	-21.487*	S=-0.574M+753.29	0.84
Margalla-99								
SW 1	1138	39	354	15	-784	-43.060*	S=-0.798M+1420.3	0.18
SW 2	1075	09	339	27	-736	-45.568*	S= 0.052M+1057.4	0.05
SW 3	907	02	308	30	-599	-34.550*	S=-0.027M+915.44	0.23
SW 4	668	28	277	37	-390	-16.267*	S=-0.473M+798.67	0.76

* Means significantly different at $P < 5\%$ level

3.5.1.3 Yield and Yield components

The primary goal of the model is to predict yield. The evaluation process for yield showed that APSIM-wheat module could not predict the wheat yield accurately using generic cultivar coefficient for the genotypes under study and showed that wheat yield is under-predicted and grain weight is over-predicted (Table 3.19 and Table 3.20).

The model under-predicted yield (Table 3.20) and over-predict grain weight (Table 3.19) of Wafaq-2001 for the data sets originated from all sowing windows with a bias of 448 – 3085 kg ha^{-1} and 0.004 – 0.012 g $seed^{-1}$, respectively. Simulated versus measured means for these two parameters were significantly different ($P < 5\%$ level).

Regarding yield of Chakwal-97, the model under-predicted for SWs 1 – 3 and over-predicted for late December sowing. The bias for under-prediction ranged from 642 to 2636 kg ha^{-1} while for SW4 it was over-predicted with a bias of 1010 kg ha^{-1}. Simulated and measured means were significantly different ($P < 5\%$ level) excluding SW3.

However, grain weight was over-predicted except for SW2 with a bias of 0.004 to 0.010 g $seed^{-1}$ and simulated means were significantly different from measured means (Table 3.19 and Appendix 35).

The model under-predict both yield and grain weight of NR-55 with a bias of 132 to 1104 kg ha^{-1} and 0.003 to 0.014 g $seed^{-1}$. Using generic cultivar coefficients, the model under-predicted yield (with a bias of 1241 to 2943 kg ha^{-1}) and over-predict grain yield (showing a bias of 0.001 to 0.006 g $seed^{-1}$) of NR-232. All the simulated

Table 3.18 Comparison of simulated and measured values♕ regarding biomass (*kg ha⁻¹*).

Sowing Windows (SW)	Measured		Simulated		Bias	*T*	Regression Equation	r^2
	Mean	SD	Mean	SD				
Biomass (kg ha^{-1})								
				Wafaq-2001				
SW 1	14472	1575	3839	265	-10633	-11.530*	S= 5.520M-6720.5	0.86
SW 2	12028	1119	4612	487	-7416	-10.526*	S=-1.959M+21062	0.73
SW 3	9654	627	4333	744	-5321	-09.474*	S=-0.171M+10394	0.04
SW 4	4356	1773	4351	633	-5	-0.0049	S= 2.003M-4360	0.51
				Chakwal-97				
SW 1	15069	1174	4290	328	-10149	-14.419*	S= 0.133M+14417	0.00
SW 2	12528	977	5933	548	-6594	-10.200*	S=-1.676M+22470	0.88
SW 3	9463	1298	5380	741	-4084	-04.735*	S= 0.973M+4228	0.31
SW 4	3373	1093	5283	685	-1910	03.203*	S= 0.903M-1396	0.64
				NR-55				
SW 1	11398	712	6582	351	-4685	-10.506*	S= 2.012M-1842.8	0.98
SW 2	10378	317	7180	551	-3430	-08.709*	S=-0.389M+13167	0.46
SW 3	7398	585	6475	742	-1598	-01.693	S=-0.242M+8964	0.09
SW 4	4154	213	6009	912	1969	03.432*	S= 0.222M+2818	0.90

♕ Arithmetic means and standard deviation (SD), bias, t statistics, regression equations of simulated (S) and measured (M) values, and coefficient of determination (r^2) for biomass (*kg ha⁻¹*).

* Means significantly different at $P < 5\%$ level

Table 3.18 Continued......

Sowing Windows (SW)	Measured		Simulated		Bias	t	Regression Equation	r^2
	Mean	SD	Mean	SD				
Biomass (kg ha^{-1})								
NR-232								
SW 1	15750	834	5476	388	-10275	-19.358*	S=-0.314M+17469	0.02
SW 2	14233	483	5952	553	-8281	-19.537*	S=-0.466M+17004	0.28
SW 3	9583	500	5380	741	-4203	-08.148*	S= 0.102M+9037	0.02
SW 4	3250	575	5283	685	1948	4.360*	S=-0.169M+4230	0.10
NR-234								
SW 1	16000	118	7386	250	-8614	-38.919*	S= 0.400M+13077	0.26
SW 2	13167	1414	6381	878	-6786	-06.281*	S= 1.806M+2351	0.73
SW 3	10709	59	5194	802	-5514	-44.286*	S=-0.324M+12241	0.20
SW 4	2917	285	4926	766	2083	07.871*	S= 0.375M+1157	0.35
Margalla-99								
SW 1	15625	766	7469	181	-8156	-24.736*	S=-0.732M+21093	0.06
SW 2	13667	118	7226	550	-6441	-20.057*	S= 0.051M+13298	0.11
SW 3	9833	236	6476	743	-3358	-07.645*	S= 0.172M+8717	0.59
SW 4	2700	600	6009	912	3624	06.507*	S= 0.335M+374	0.94

* Means significantly different at $P < 5\%$ level

and measured means for yield were significantly different ($P < 5$ % level). Similar trend was observed for NR-234. Under-prediction of yield has a bias of 1191 to 2535 kg ha^{-1}. Simulated versus measured means were significantly different except for November sowing. Grain weight was under-predicted with early sowing and over predicted with late sowing (Table 3.19 and Appendix 35).

APSIM-wheat module under-predicted yield of Margalla-99 except for late sowing in December. Simulated and measured means for three SWs were significantly different ($P < 5$ % level) with a bias of 298 – 2212 $kgha^{-1}$ (Table 3.20 and Appendix 36).

With grain weight generally over-predicted, the model under-predict the yield of these genotypes with a highest bias of 3085 kg ha^{-1} for Wafaq-2001. For all genotypes the model over-predicted the yield with late sowings in December. Deviations in simulating yield from measured values suggested that adjustments in the cultivar coefficients may be required to have a good agreement between simulated and measured yield.

Table 3.19 Comparison of simulated and measured values⇮ regarding grain weight ($g\ seed^{-1}$).

Sowing Windows (SW)	Measured		Simulated		Bias	*t*	Regression Equation	r^2
	Mean	SD	Mean	SD				
Grain weight (g seed^{-1})								
Wafaq-2001								
SW 1	0.041	0.002	0.046	0.001	0.005	4.00*	S=-1.5M+0.1105	0.75
SW 2	0.038	0.002	0.043	0.001	0.005	4.43*	S= 1.5M-0.026	0.25
SW 3	0.030	0.004	0.042	0.002	0.012	4.18*	S= 1.46M-0.032	0.46
SW 4	0.036	0.002	0.041	0.003	0.004	2.34	S=-0.21M+0.045	0.99
Chakwal-97								
SW 1	0.039	0.002	0.043	0.001	0.004	3.11*	S=-1.185M+0.0893	0.10
SW 2	0.039	0.002	0.037	0.002	-0.002	-1.37	S=-1.150M+0.0816	0.98
SW 3	0.030	0.003	0.039	0.004	0.010	3.54*	S= 0.681M+0.0029	0.58
SW 4	0.032	0.001	0.037	0.006	0.005	1.52	S=-0.098M+0.036	0.93
NR-55								
SW 1	0.044	0.001	0.037	0.002	-0.006	-5.910*	S=-0.6M+0.0663	0.81
SW 2	0.045	0.000	0.032	0.001	-0.014	-19.325*	S=0.34M+0.0346	0.87
SW 3	0.036	0.001	0.032	0.003	-0.003	-2.030	S= 0.25M+0.0278	0.89
SW 4	0.033	0.001	0.035	0.005	0.002	0.709	S=-0.091M+0.833	0.83

⇮Arithmetic means and standard deviation (SD), bias, t statistics, regression equations of simulated (S) and measured (M) values, and coefficient of determination (r^2) for grain weight ($g\ seed^{-1}$)
* Means significantly different at $P < 5\%$ level

Table 3.19 Continued......

Sowing Windows (SW)	Measured		Simulated		Bias	t	Regression Equation	r^2
	Mean	SD	Mean	SD				
Grain weight (g seed^{-1})								
NR-232								
SW 1	0.041	0.002	0.042	0.000	0.001	0.527	S=0.0413	0.00
SW 2	0.038	0.000	0.037	0.002	-0.001	-0.906	S=0.058M+0.036	0.43
SW 3	0.035	0.004	0.039	0.004	0.004	1.235	S=-1.173M+0.0816	0.99
SW 4	0.031	0.002	0.037	0.006	0.006	1.820	S=0.340M+0.0183	0.94
NR-234								
SW 1	0.040	0.002	0.031	0.002	-0.009	-4.224*	S=-1.65M+ 0.0929	0.99
SW 2	0.037	0.001	0.037	0.003	-0.001	0.037	S=-0.372M+0.0514	0.99
SW 3	0.037	0.005	0.040	0.003	0.004	0.746	S=-1.122M+0.0815	0.99
SW 4	0.029	0.002	0.039	0.005	0.011	2.108	S=0.3333M+0.0157	0.99
Margalla-99								
SW 1	0.040	0.001	0.030	0.002	-0.010	-9.422*	S=-0.45M+0.0531	0.43
SW 2	0.034	0.007	0.032	0.001	-0.003	-0.852	S=0.0342	0.00
SW 3	0.032	0.005	0.032	0.003	0.000	0.0127	S=1.05M-0.0016	0.75
SW 4	0.030	0.001	0.035	0.005	0.005	1.7357	S=-0.0665M+0.0318	0.47

* Means significantly different at $P < 5\%$ level

Table 3.20 Comparison of simulated and measured values regarding yield (*kg ha⁻¹*).

Sowing Windows (SW)	Measured		Simulated		Bias	*T*	Regression Equation	r^2
	Mean	SD	Mean	SD				
Yield (kg ha⁻¹)								
Wafaq-2001								
SW 1	4707	710	1623	118	-3085	-7.423*	S=3.363M-750.44	0.31
SW 2	4297	635	1883	189	-2414	-6.311*	S=-2.236M+8506.8	0.44
SW 3	3074	316	1775	295	-1299	-5.205*	S=1.0453M+1218.6	0.95
SW 4	1280	693	1728	274	448	1.0414	S=2.2317M-2576.3	0.78
Chakwal-97								
SW 1	4633	428	1996	120	-2636	-10.28*	S=1.7808M+1077.6	0.25
SW 2	4057	151	2225	145	-1832	-15.19*	S=0.9332M+1980.8	0.81
SW 3	2723	305	2081	310	-642	-2.557	S=0.7792M+1101.9	0.63
SW 4	976	413	1985	331	1010	3.301*	S=1.237M-1479.5	0.98
NR-55								
SW 1	2604	311	2423	88	132	-0.975	S=1.031M+106.89	0.09
SW 2	3217	305	2385	141	-673	-4.278*	S=1.756M-970.8	0.66
SW 3	1735	150	2197	320	609	2.265	S=0.458M+728.05	0.95
SW 4	1109	62	2144	445	1104	3.989*	S=0.1078M+877.4	0.60

ÎArithmetic means and standard deviation (SD), bias, t statistics, regression equations of simulated (S) and measured (M) values, and coefficient of determination (r^2) for yield

* Means significantly different at $P < 5\%$ level

Table 3.20 Continued......

Sowing Windows (SW)	Measured		Simulated		Bias	T	Regression Equation	r^2
	Mean	SD	Mean	SD				
Yield (kg ha^{-1})								
NR-232								
SW 1	5155	338	2213	164	-2943	-13.59*	S=-0.48M+6223	0.06
SW 2	4475	45	2233	143	-2242	-25.98*	S=0.092M+4270	0.09
SW 3	3323	383	2081	310	-1241	-4.366*	S=-0.30M+3944	0.06
SW 4	795	40	1985	331	1190	6.180*	S=0.074M+649	0.37
NR-234								
SW 1	4901	342	2365	60	-2535	-10.34*	S=-15.98M+43238	0.99
SW 2	3685	1082	2329	205	-1355	-1.89	S=7.381M-12753	0.99
SW 3	3247	33	2056	335	-1191	-39.54*	S=0.906M+1557.6	0.99
SW 4	653	30	1934	364	1281	25.42*	S=0.5335M-268	0.99
Margalla-99								
SW 1	4550	552	2338	64	-2212	-9.685*	S=5.295M-7830	0.74
SW 2	3590	368	2358	117	-1233	-7.484*	S=1.140M+912	0.26
SW 3	2496	998	2197	320	-298	-0.667	S=2.129M-2183	0.93
SW 4	451	63	2144	445	1693	6.5505*	S=0.099M+239	0.98

* Means significantly different at $P < 5\%$ level

3.5.2 Parameterization of APSIM-Wheat Module

Wheat growth and development in APSIM-Wheat module respond to weather and management conditions through a set of cultivar coefficients. Treatments from each data set which experienced no or limited water stress were used for model parameterization. Coefficients resulting in a good fit between simulated and measured values were maintained at their original values. The model was run for the same location and treatment(s) to examine the goodness-of-fit between the predicted and measured values regarding phenology, biomass, grain weight and yield by increasing or decreasing, using a small step, the values of cultivar coefficients not in a good fit between simulated and measured data (Appendix 1) .

3.5.2.1 Crop Phenology and Morphology

Using the modified coefficients (Appendix 1) good agreement was obtained between all the simulated outputs and measured values regarding anthesis date, maturity date and plant height. Mean simulated and measured responses across sowing windows and genotypes were comparable with bias within 1.00 for anthesis date, 1.75 for maturity date and 8.83 for plant height (Appendix 37). Non-significant differences between the simulated and measured means were found for these parameters.

Regarding days to anthesis, the slope of the regression equation was less than 1.0 (Chakwal-97 and NR-55) and was slightly greater than 1.0 in the case Wafaq-2001 (Figure 3.13 & Appendix 37). Regarding maturity the slope of the regression equation was slightly greater than 1.0 for Chakwal-97 and less than 1.0 for Wafaq-2001 and NR-55 (Figure 3.14 & Appendix 37). In the case of plant height (Figure 3.15 & Appendix 37) slope of the regression equation was slightly greater than 1.0 for all

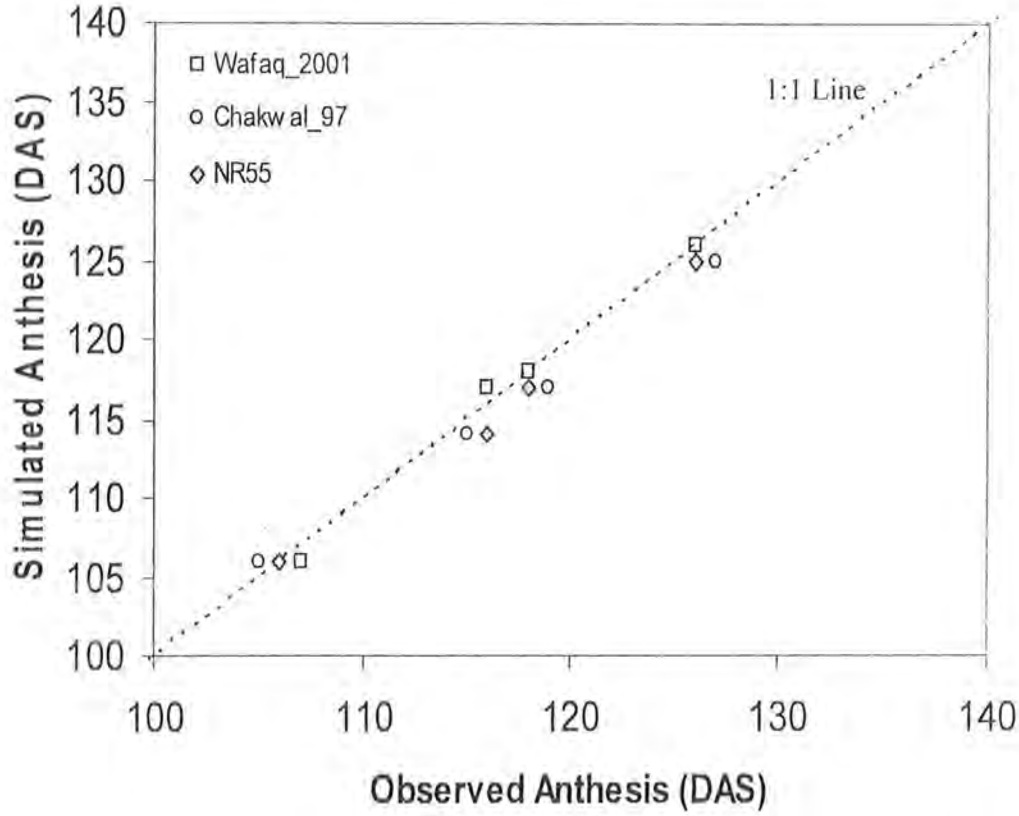

Figure 3.13 Comparison of simulated and measured anthesis (*Days after Sowing*) across sowing windows 1, 2, 3 and 4.

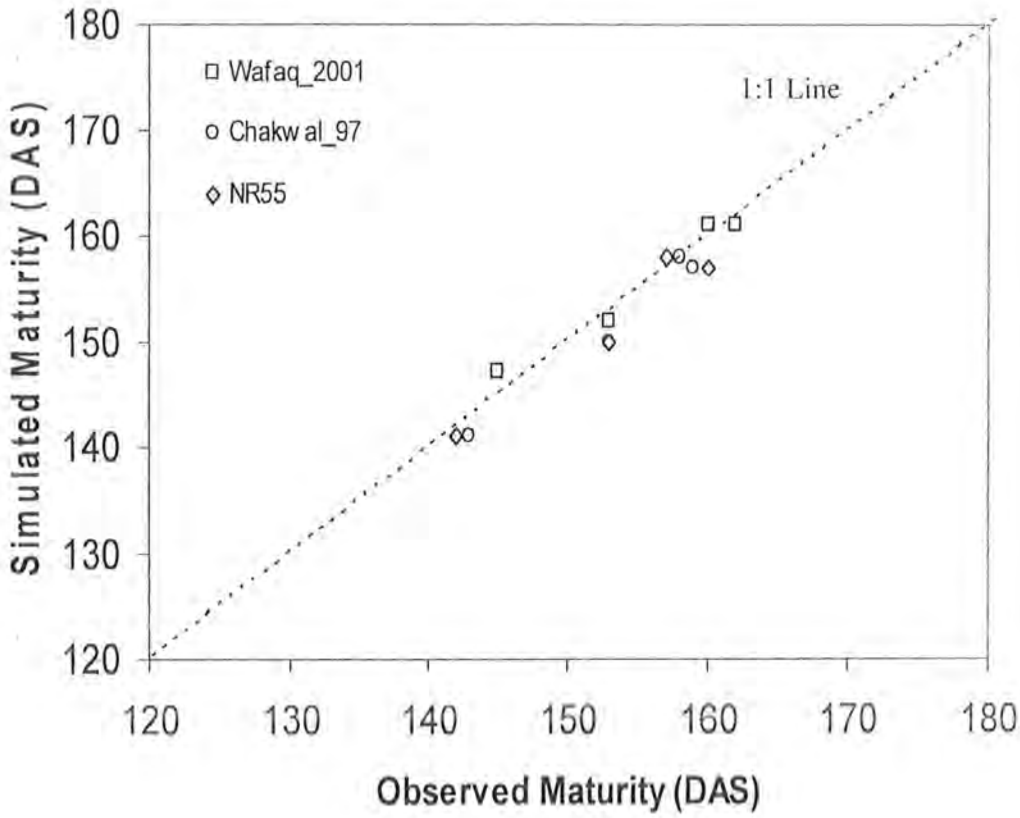

Figure 3.14 Comparison of simulated and measured maturity (*Days after Sowing*) across sowing windows 1, 2, 3 and 4.

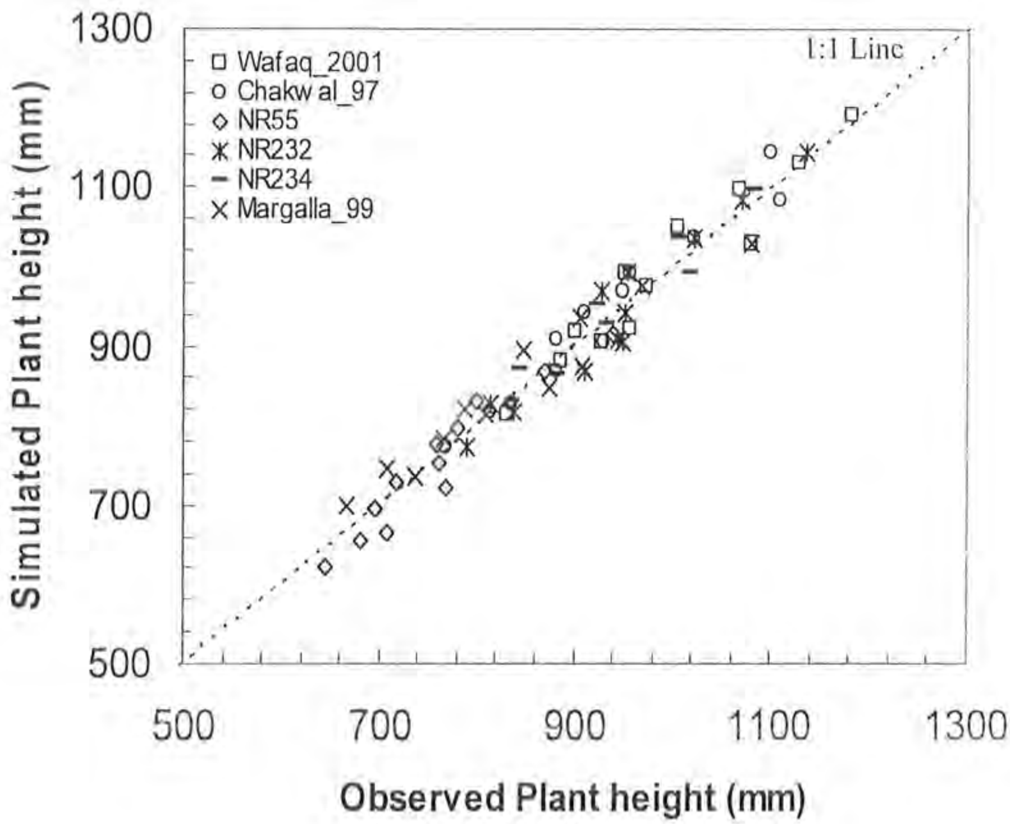

Figure 3.15 Comparison of simulated and measured plant height (mm) across sowing windows 1, 2, 3 and 4.

genotypes, except Margalla-99 (Appendix 37).

Use of the modified coefficients made it convenient in improving the simulated phenology and morphology of wheat genotypes. This goodness-of-fit between simulated and measured values enabled the model to better simulate the biomass accumulation and partitioning during the plant's life cycle by better simulating the growth and development of the plant which ultimately enhances the model's ability to simulate the yield.

3.5.2.2 Biomass

With modified coefficients, the simulated and measured biomass compared accurately across all the sowing windows and genotypes with a bias within 272. The slope of the regression equation was less than 1.0 for Wafaq-2001, Chakwal-97 and NR-55 while it was slightly greater than 1.0 for NR-232, NR-234 and Margalla-99 (Appendix 38 and Figure 3.16). Differences between simulated and measured means were non-significant ($P < 5\%$ level). Simulated values for biomass across SWs showed an under-prediction of biomass production in all genotypes. Maximum variation was observed in case of genotype NR-232 with an under-prediction of 4%. Under-predicted simulated values varied by 1% (Margalla-99) and 2% (Wafaq-2001, Chakwal-97, NR-55 and NR-234) from measured values for other genotypes.

3.5.2.3 Yield and Yield components

Mean simulated value for yield across SWs was within a bias of about 129 (Appendix 39 and Figure 3.17). Differences between simulated and measured means were non-significant ($P < 5\%$ level).

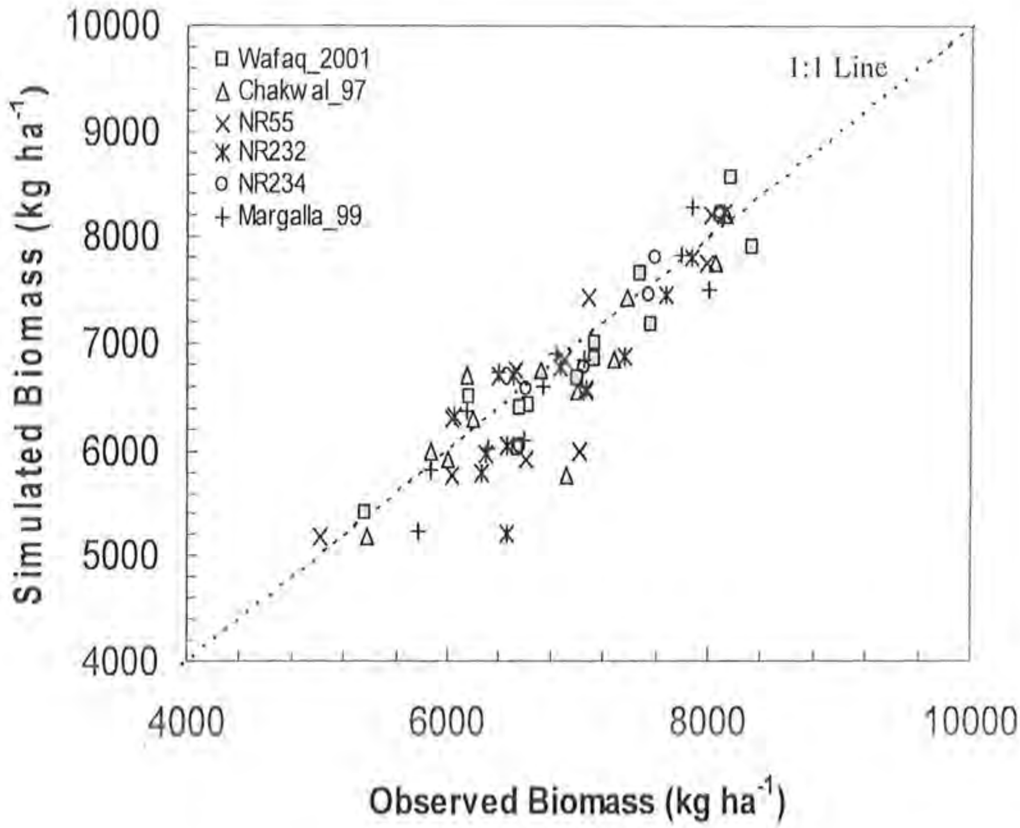

Figure 3.16 Comparison of simulated and measured biomass (kg ha^{-1}) across sowing windows 1, 2, 3 and 4.

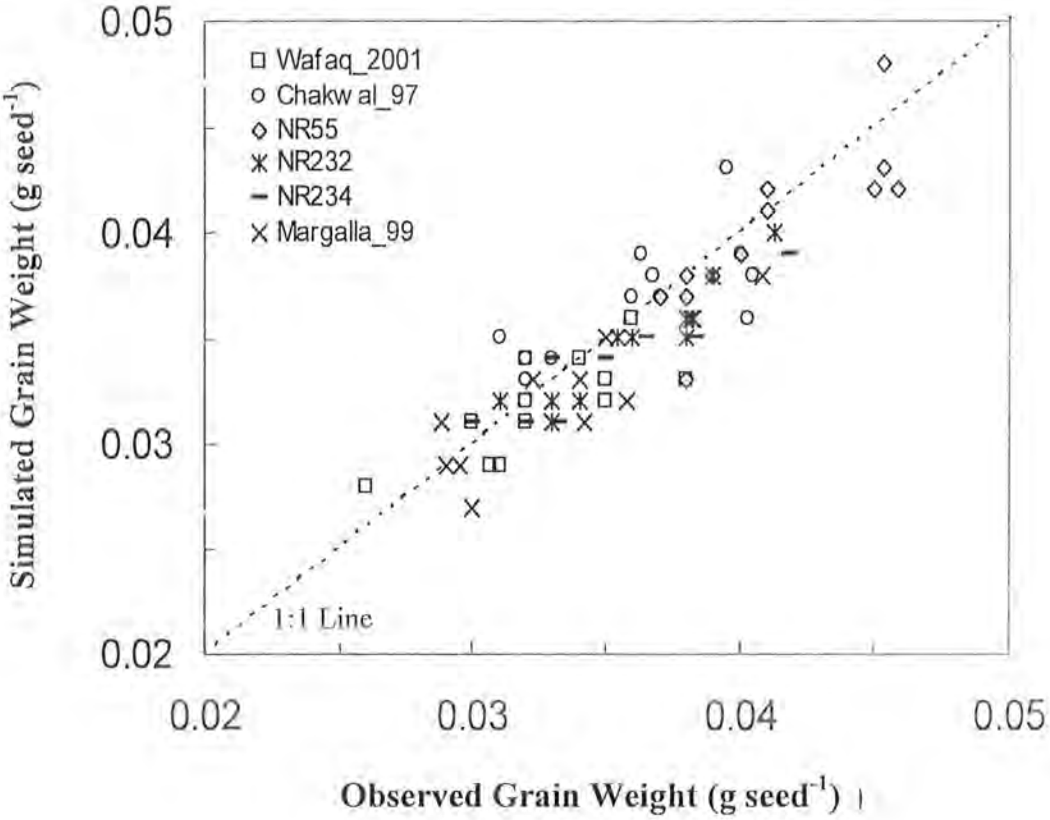

Figure 3.18 Comparison of simulated and measured grain weight (g seed^{-1}) across sowing windows 1, 2, 3 and 4.

Simulated values showed an under-prediction of yield for Wafaq-2001, Chakwal-97 and NR-234, and varied by 2% from measured values. However, for NR-232 and Margalla-99, the simulated output showed an over-prediction of 4% from measured values.

The differences between the mean simulated and measured grain weight across sowing windows were non-significant (Appendix 38 and Figure 3.18) with a bias within 0.001 across all the cultivars. The slope of the regression equation was less than 1.0 for all genotypes.

In the parameterization process, the modified cultivar coefficients accurately regulated the phasic development of the genotypes used in this study which lead to goodness-of-fit between simulated and measured values regarding the occurrence of anthesis and maturity. This improvement in the model's performance with parameterized cultivars also improved the biomass accumulation and yield in these genotypes across sowing windows. These results developed confidence in the APSIM-wheat module, and it enhanced the utilization of this bioinformatics tool for strategic management decisions regarding wheat crop sown under rainfed conditions of Pothowar area.

3.6 APSIM MODEL UTILIZATION

3.6.1 RAINFALL PATTERN OVER TIME IN RAINFED AREA

Two distinct rainfall patterns are observed in rainfed areas of Islamabad (Figure 3.19). One as summer, which is locally called as kharif season starting from June and extended until September and other as winter, locally known as rabi season, the duration of which is from October to May. Actual rainfall data was plotted in an aggregated polynomial format, aggregated over a span of 3 years and each data point with a range bar. The analysis of long term rainfall data of Islamabad over 47 years (1961-2007) using STATISTICA revealed that in the rainfed area of Islamabad, about 60 % rainfall occurred during summer and 40 % during winter season (Figure 3.19). Analysis also revealed that the long-term rainfall pattern are showing increasing trends in case of occurrence of summer rainfall in rainfed areas whereas, it showed a slight decreasing trend in winter rainfall over this period of 47 years (Figure 3.19). During summer period it is observed that rainfall intensity in the month of July has increased overtime whereas, the month of September has shown a decrease in rainfall intensity. This September rainfall decrease is of great concern as it could provide better residual moisture for sowing of wheat during October (Figure 3.20).

3.6.2 STUDY ON RAINFALL PATTERN OVER TIME USING APSIM MODEL

The Southern Oscillation, which is a see-saw of air pressure between the west and east tropical Pacific, has an important influence on rainfall in many regions of the world particularly monsoonal regions in terms of the onset and end of monsoon and the amount of rainfall likely to be received during the season. A regularly occurring cycle of Southern Oscillation Index (SOI), reflecting the air pressure between Darwin and Tahiti, can be utilized for climatic predictions particularly rainfall up to couple of

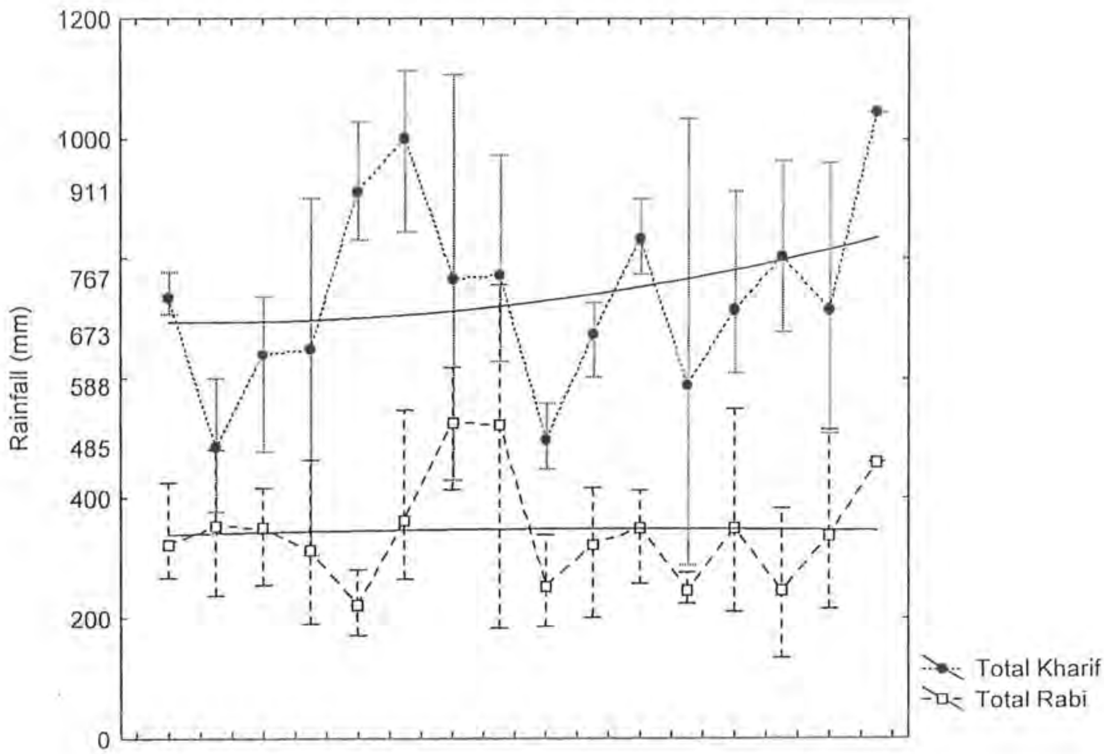

Figure 3.19 Long term rainfall pattern in Islamabad over time (1961-2007).

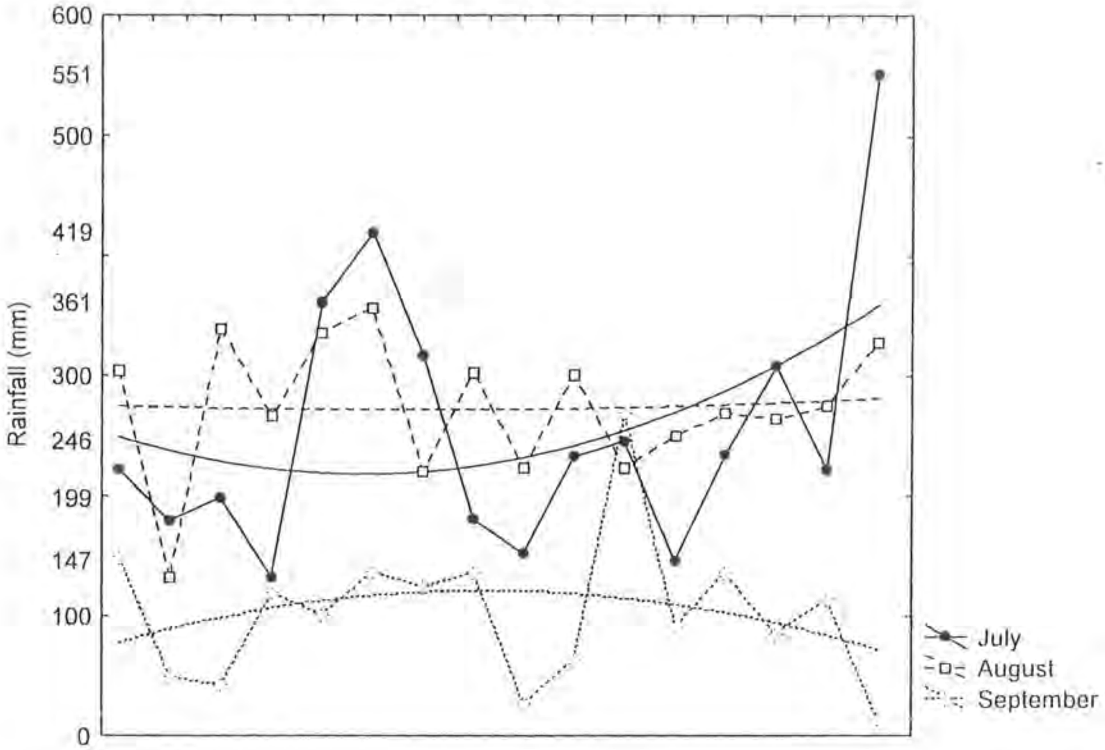

Figure 3.20 Long term rainfall pattern in Islamabad during the months of July, August and September from 1961-2006. Actual rainfall data was plotted in an aggregated polynomial format, aggregated over a span of 3 years.

years. It has an average cycle of four years but strong negative and positive phases of SOI could occur at three to six years' interval as El Niño and La Niña events.

The long term weather data (1961-2007) of Islamabad was also analyzed using APSIM model. The purpose of this analysis was to study the relationship between Southern Oscillation Index (SOI) phases and the pattern of weather change due to these SOI phases under rainfed conditions of Islamabad. The model has already been provided the facility to work with SOI phases as an index of such analysis. The results given in figure 3.21 indicated that the July SOI phases and the rainfall variability during October-November (the sowing time of wheat) have a positive link among each other. The analysis also indicated that, based on long term rainfall data (1961-2007), the Islamabad zone has 44% and 35% possibility of exceeding median rainfall with consistently near zero and consistently negative SOI phases, respectively during July.

3.6.3 STUDY ON YIELD BEHAVIOR OF WHEAT USING APSIM MODEL

The APSIM model was used to analyze the impact of SOI phases on wheat yield of various genotypes over variant SWs for Islamabad area (Figure 3.22 and 3.23). The simulation analysis regarding partitioning of wheat yield, averaged across sowing windows, using SOI phases were performed. It showed that sowing after mid November (SW3 and SW4) was vulnerable to climatic fluctuations governed by SOI phase in July. It was mainly due to probability of occurrence of rainfall at the growth stage of crop establishment. The simulation studies clearly depicted that the yield increased to about 1 t/h with the SOI phase 3 during July as compared to phase 5 during the same month. It predicted that rainfall received in relation to crop

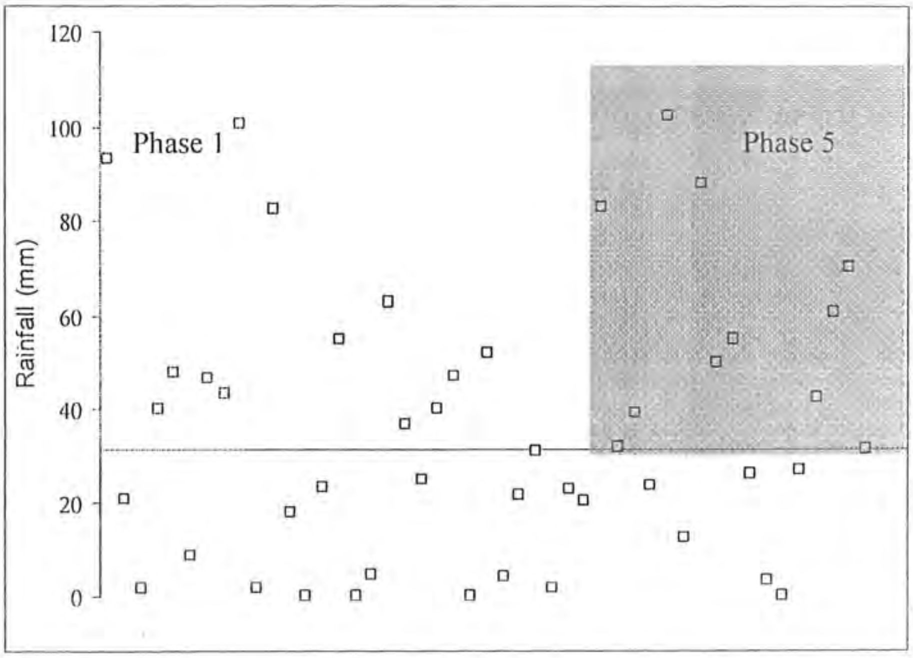

Figure 3.21 Relationship between rainfall occurrence variability during October-November and monthly SOI phase in July. Analysis was done using actual rainfall during 1961-2007. The horizontal line indicated median rainfall for that period.

phenological stage is efficiently utilized compared to other sowing windows in SOI phase 3. The simulation results also showed that prevalence of SOI phase 2 and 3 explains less yield depressions in all varieties under study in rainfed areas compare to other patterns of SOI phases. This type of knowledge may be used to decide for the sowing of wheat if information about these phases is known prior to start of wheat sowing in the area.

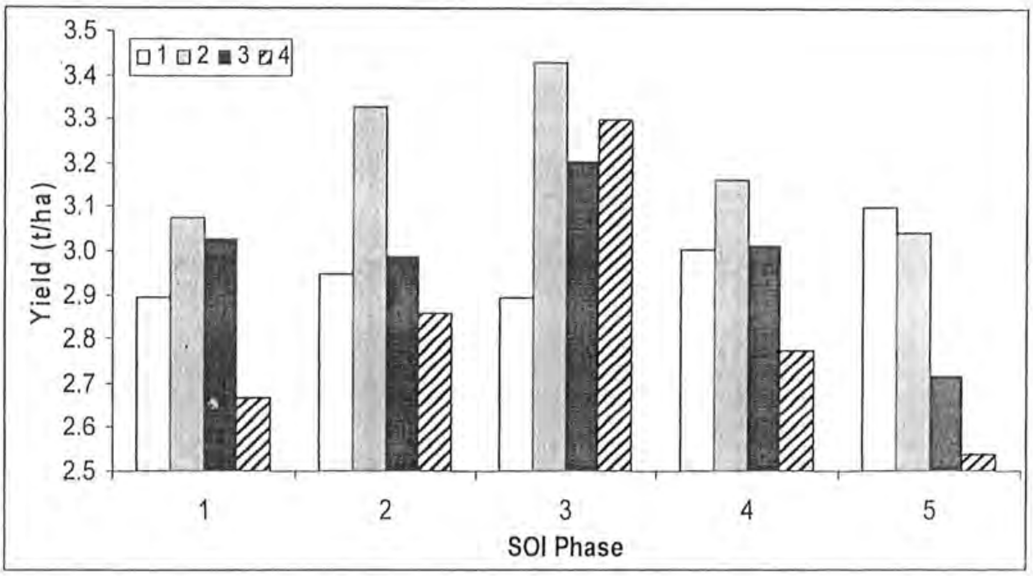

Figure 3.22 Simulated wheat yield over years (1961-2007) for Islamabad partitioned against July SOI phases and averaged across sowing windows (1, 2, 3, & 4).

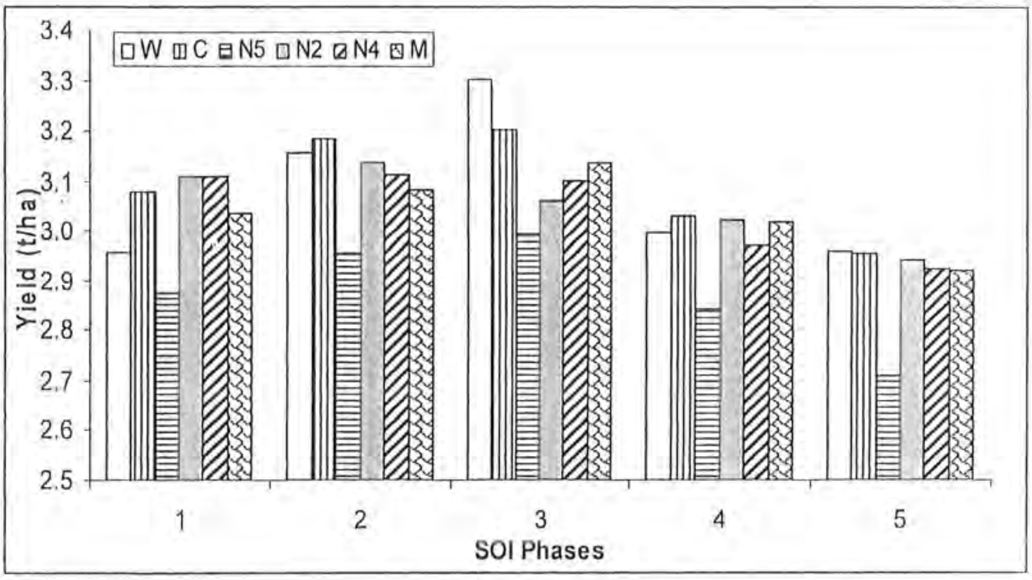

Figure 3.23 Simulated wheat yield over years (1961-2007) for Islamabad partitioned against July SOI phases and averaged across genotypes.

Figure 3.24 A view of wheat crop (taken at the end of December) sown at different times in the field

DISCUSSION

CHAPTER 4

DISCUSSION

4.1 PERFORMANCE OF WHEAT GENOTYPES OVER SOWING TIMES

The studies have depicted that variation in climatic parameters have a very significant effect on performance of wheat crop in rainfed areas. The wheat sowing windows have shown that by bringing variation in sowing time the weather variation could be better managed or utilized. All the genotypes under study responded in similar fashion to climatic variables.

Wheat yield reduction by delaying sowing time from sowing during 15-25 October (SW1) to sowing during 10-17 November (SW2) was around 10 %. However, a yield reduction of 66 % was observed with sowing during 10-24 December (SW4) producing a 60 kg/ha/day reduction across the genotypes under study for this area due to reduction in crop growth, development and yield components. Among these components biomass, number of spikelets per spike, and 1000 grain weight were the most important predictors of yield. Similar findings are also reported by Asif *et al.*, (2003) in which a positive correlation of grain yield was shown with 1000 grain weight and being an important indicator of grain yield, 1000 grain weight should be considered in breeding programmes.

In the studies it was observed that above ground biomass reduced up to 50 % in SW4 as compared to SW1. This reduction in biomass is due to a linear reduction, of up to 79 %, observed in tiller production across the genotypes in this study (Slafer *et al.*, 1993).

Similarly pattern of biomass accumulation in the present study revealed a considerably different pattern in and across all the genotypes sown in SW3. This lag phase in the pattern could be explained from the climatic factors during the wheat growing season in this area where temperature gradually declines from the end of November to January (Appendix 30). In this study over time, it has been observed that during the crop growth cycle dense clouds remained there but rain did not occur and this situation prevailed for several weeks resulting in reduced bright sunshine hours and solar radiation. This impedes crop growth and development due to low photo-synthetically active radiations being received by the crop during its vegetative growing phase and may have ultimately affected the grain yield.

Spikelets number per spike determines the number of grains per spike and the grain number per unit area (Slafer *et al.*, 1993). However, unlike grain number, little relationship has been reported between grain weight and grain yield. Frederick and Bauer (2000) described a very close relationship between grain yield and grain number per m^2. The significant contribution of grain weight towards grain yield in present study might be due to the prolonged period of vegetative growth and may have direct effects of anthesis and maturity *(Days after sowing)* by utilizing the photosynthate made prior to anthesis. Under such a condition, photosynthates availability would not be a limiting factor, and the photosynthate made prior to anthesis significantly contributed towards grain yield as explained by Bidinger *et al.*, (1977) and there would be no competition of photosynthate supply or assimilate partitioning among individual grains mentioned in studies by Asif *et al.*, (2003), Singh and Singh (2001) and Dokuyucu and Akkaya (1999). The other possibility may be that grain number produced were below potential and as a result of reduction in grain number per spike may have compensated towards more grain weight and ultimately contributed significantly towards grain yield. These findings are in line with the results reported by Frederick and Camberato (1995).

4.2 GENOTYPE X ENVIRONMENT X MANAGEMENT (G X E X M) INTERACTION

The results of analysis of variance have revealed that the most significant component of G x E x M interaction for wheat yield was management factor especially sowing windows (M). The significance of this factor reflects the importance of sowing time and the fact that the selection of optimum sowing time would determine the successful completion of the crop's life cycle in a given environment of rainfed agriculture. Similar findings have been reported by Dennett (2000) in which he included the moderate climatic conditions, such as favorable temperatures, and sufficient water supply. Water availability in the form of rainfall is of immense importance particularly under rainfed conditions. Under rainfed environment, the dominating factors for the choice of optimum sowing time included available soil moisture and the patterns of rainfall received which governed the crop establishment by affecting the germination and emergence.

The study have clearly indicated that the selection of optimum sowing time would also help to ensure the sufficient duration of time for tiller initiation and adequate number of tillers per m^2 will result in establishment of good crop stand. The results also depict that optimum sowing time of wheat under rainfed environment also results in increasing grain yield due to the favorable environmental conditions prevailed during grain filling period. Data also revealed that in spite of the variations in sowing time, all the genotypes under study reached at maturity stage within same span of time. This showed the importance of selecting suitable genotypes which could perform better to cope with the seasonal variation and produce optimum grain yield irrespective of the time taken to maturity. These findings are in corroboration with Muchow *et al.*, (1994) and Aggarwal and Kalra (1994). It is suggested that further studies could be under taken on performance of cultivars by sowing them at early sowing time. In such studies, long-season cultivars may be included to evaluate in case of early rains occurrence. Similarly short-duration cultivar may be studied in case of delayed occurrence of rains. It is further suggested that in such studies use of seasonal climate forecasting based on SOI phases may be incorporated for selection of optimum sowing time and suitable cultivar. This could be better explained by using crop simulation modeling in conjunction with seasonal forecasting to assist in decision making based on eco-physiological explanations (Meinke *et al.*, 1996; Meinke *et al.*, 2001).

4.3 PARAMETERIZATION AND EVALUATION OF APSIM-WHEAT MODULE

Model validation against independent data set is an essential step in model use for various scenario analyses (Dent *et al.*, 1979). The perfection of model validation requires that a validated crop simulation model could give accurate prediction of crop phenology, biomass production, and yield of the wheat crop in a given environment with a set of real management practices i.e., time of sowing, soil type, cultivar used and available moisture etc.

Accordingly in these studies, the evaluation of the model was carried out with the actual observations made from the wheat crop grown under local conditions using various sowing windows. In the study the cultivar genetic coefficients were calibrated to have a goodness-of-fit between simulated and measured values of crop growth and development. Using the model in built generic cultivar coefficients the model was unable to track accurately the crop phenological events according to the actual observations made in the field. For example, the occurrence of anthesis and maturity was either under-estimated or over-estimated as compared to measured values for the 6 genotypes. These variations were because of the reason that in APSIM-Wheat module the start and end of each phenological stage is determined by thermal time which is ultimately affected by vernalisation and photoperiod. Accordingly in these studies the sensitivities to photoperiod and vernalisation which are cultivar specific were re-adjusted to make the model accurate in predicting crop phenological stages particularly occurrence of anthesis and maturity. Similar work has been reported on spring wheat phenological development by Perry *et al.*, (1987), Handoko (1992), O'Leary (1994) and Asseng *et al.*, (1998). In the present study the use of modified cultivar genetic coefficients made it possible to build a confidence in APSIM-Wheat module to simulate the crop phenology with non-significant differences (at $P <$ 5% level) in simulated and measured values.

Similarly, the model also under-estimated the plant height. In APSIM, the plant height is a function of stem weight per plant. Since, the simulated biomass was also not in a good agreement with measured biomass, so it required an adjustment in the coefficients to predict biomass, plant height and yield. In the process of validation, the adjustments in the radiation use efficiency (as it affected the biomass accumulation calculated from intercepted radiations) and as a result plant height against stem weight achieved a good fitness and non-significant differences were found between simulated biomass production, plant height and yield compared to real values observed in the field. With these adjustments confidence was built in the APSIM-wheat module and ultimately it proved as a bioinformatics tool which was utilized in the present studies to better understand wheat crop performance in rainfed conditions and also use it for tactical management decisions regarding sowing windows of wheat.

4.4 APSIM MODEL UTILIZATION

In the present studies, the parameterized APSIM model was used as a tool for selecting optimum sowing time and cultivar and also the resilience in cropping systems against climatic variability. The significance of similar exercise has been reported by Aggarwal *et al.* (1994), Hunt *et al.* (1996), Meinke *et al.* (1997) and many others. In these studies, there has been considerable progress made in the field of seasonal climate forecasting and the use of this skill in selecting optimum sowing time and suitable cultivar coupled with crop simulation models. The study provided help to study the impact of El Niño Southern Oscillation (ENSO) on rainfall patterns and temperature variability under rainfed environment of

Islamabad. Stone *et al.* (1993) have also used this tool to study the climatic predictions for risk assessment of wheat production else where.

While using APSIM model to study long-term rainfall data of Islamabad from 1961 to 2007, it revealed an obvious trend of increasing summer rainfall and decreasing winter rainfall over that period. The observed trends also indicated a significant tendency towards increased rainfall in July and decreased rains in September. Based on information generated the analysis revealed an opportunity of early sowing and hold true for the selection of optimum sowing time in the last week of October (sections 4.1, 4.2) as the selection of sowing time in this rainfed area depend on moisture availability. In accordance to these findings, Stone *et al.* (1996) also showed the relationship of SOI phases and rainfall variability for Australia and many other regions of the world. In the presented study, an attempt was made to evaluate the impact of SOI on rainfall variability under local environment during October-November period. The analysis using probabilistic approach revealed that, based on long term rainfall data, the Islamabad zone hadc 44% and 35% possibility of exceeding median rainfall with consistently near zero and consistently negative SOI phases, respectively during July. Further work is required on multiple locations to establish this link of rainfall variability with SOI phases, so that seasonal forecasting could be used operationally for better synthesis of management decisions.

Generation of information for multiple locations using phases of the SOI coupled with mechanistic crop simulation models will allow the manager or decision maker to better quantify the climatic risks. Similar opinion has been explained by

Meinke *et al.* (1996). The partitioning of simulated wheat yields on the basis of July SOI phases across various sowing windows revealed that, using this skill of seasonal climate forecasting based on SOI phase before start of wheat season, the optimum sowing window in this region could be depicted before time and start from the mid of October and extends until the mid of November. The studies also explained the use of crop simulation models "as 'filters' to gauge the value of rainfall over a growing season" (Meinke and Hammer, 1997; Keating and Meinke, 1998).

4.5 CONCLUSION

In these studies significant differences were observed in wheat crop performance sown over four sowing windows using six genotypes. Delay in sowing time significantly reduced the grain yield and biomass accumulation. The genotypes in respect of various growth, development and yield components behaved variably. Among these parameters biomass, number of spikelets per spike, and 1000 grain weight were the most important parameters to be used for prediction of yield for these genotypes. Sowing time as a crop management tool played a significant contribution towards the grain yield, reflecting the importance of the selection of optimum sowing time of wheat in the rainfed areas. APSIM model was evaluated and parameterized using actual climatic data of Islamabad. This validated crop simulation model was used as a tool for understanding and analyzing optimum sowing time, cultivar and climatic behavior. The simulation results showed that sowing after mid November was vulnerable to climatic fluctuations governed by Southern Oscillation Index (SOI) phase in July. A relationship of climate and wheat yield depicted that wheat yield increase of about 1 t/ha was observed when the estimates of SOI phase 3 during July were considered for prediction process of the area. Studies further highlighted more rainfall variability with 44% and 35% possibility of exceeding median rainfall with consistently near zero and consistently negative SOI phases, respectively during July. The studies have clearly verdict that crop simulation model, as an agronomic tool could be successfully used to understand crop bio-dynamism, climate and crop management simultaneously to explore the potential yield of wheat in a given environment. However, further work is suggested, to link the rainfall variability in this rainfed zone with SOI phases so that the SOI based seasonal forecasting could be used to have a tactical management decision for the optimal wheat sowing window and suitable cultivars on multiple locations to use simulation technique comprehensively. The evaluation of model over multiple locations will enhance our knowledge to pick variability in various rainfall and temperature regimes and prove a better tool for wheat yield forecasts of these areas.

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APPENDICES

APPENDICES

Appendix 1. Physico-Chemical characteristics of the experimental site

	Units	Values		
		0-15 cm	**15-30 cm**	**30-45 cm**
pH	1:1	8.3	8.2	8.4
EC	dSm^{-1}	0.20	0.22	0.23
N	%	0.04	0.03	0.03
$CaCO_3$	%	14.0	12.0	12.0
Organic C	%	0.29	0.27	0.18
Silt	%	74.4	72.4	72.0
Sand	%	15.1	12.9	12.7
Clay	%	10.5	14.7	15.3
Bulk Density	g/cm^3	1.60	1.57	1.46
Soil Lower Limit (15 bar)	mm/mm	0.08	0.10	0.11
Soil Drain Upper Limit	mm/mm	0.28	0.31	0.31
Saturated Soil Water	mm/mm	0.34	0.36	0.41
Soil Albedo (value taken from model)		0.13		

Appendix 2. Cultivar parameters for wheat crop modified during APSIM-Wheat module parameterization

Parameter	Default value in APSIM-wheat	Wafaq-2001	Chakwal-97	NR-55	NR-232	NR-234	Margalla-99
Vernalisation sensitivity	1.5	0.0	0.0	0.0	0.0	0.0	0.0
Photoperiod sensitivity	3.0	3.5	3.5	3.5	3.5	3.5	3.5
Thermal time for grain filling	580	700	634	634	634	634	634
Stem weight / height (g m^{-2}) / mm	6/1500	1.4/1200	1.8/1500	1.8/1500	1.8/1500	1.8/1500	1.8/1500
Radiation use efficiency at floral initiation/flowering	1.24/1.24	3.00/2.24	3.00/2.24	3.00/2.24	3.00/2.24	3.00/2.24	3.00/2.24

Appendix 3. Analysis of Variance (ANOVA) for testing the significant differences between biomass accumulation rates during sowing window 1 at various crop growth stages⌂

	At 3 leaf stage	*At anthesis stage*	*At maturity*
SS (replicates)	0.001	0.007	0.008
SS (genotypes)	0.079	61.283	226.052
SS (error)	0.003	0.021	0.023
MS (replicates)	0.001	0.003	0.004
MS (genotype)	0.016	12.257	45.210
MS (error)	0.001	0.002	0.002
F. value (replicates)	2.792 NS	1.551 NS	1,650 NS
F. value (genotypes)	61.909***	5817.969***	19867.812 ***

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level, * Significant at $P < 10\%$ level, NS= Non-Significant

⌂Studied for 6 genotypes during 2001-2005 wheat growing seasons. Analysis was done using MSTATC version 1.42 using one factor RCBD model.

Appendix 4. Analysis of Variance (ANOVA) for testing the significant differences between biomass accumulation rates during sowing window 2 at various crop growth stages♕

	At 3 leaf stage	*At anthesis stage*	*At maturity*
SS (replicates)	0.001	5.729	0.001
SS (genotypes)	0.495	21.669	3.381
SS (error)	0.005	27.223	0.005
MS (replicates)	0.001	2.865	0.001
MS (genotype)	0.099	4.334	0.676
MS (error)	0.001	2.722	0.001
F. value (replicates)	0.037 NS	1.052 NS	0.377 NS
F. value (genotypes)	216.701***	1.592 NS	1239.357 ***

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level, * Significant at $P < 10\%$ level, NS= Non-Significant

♕Studied for 6 genotypes during 2001-2005 wheat growing seasons. Analysis was done using MSTATC version 1.42 using one factor RCBD model.

Appendix 5. Analysis of Variance (ANOVA) for testing the significant differences between biomass accumulation rates during sowing window 3 at various crop growth stages⇑

	At 3 leaf stage	*At anthesis stage*	*At maturity*
SS (replicates)	0.001	0.001	0.009
SS (genotypes)	0.037	15.718	115.952
SS (error)	0.004	0.014	0.018
MS (replicates)	0.001	0.001	0.004
MS (genotype)	0.007	3.144	23.190
MS (error)	0.001	0.001	0.002
F. value (replicates)	0.709 NS	0.077 NS	2.336 NS
F. value (genotypes)	20.644***	2302.022***	12695.4555 ***

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level, * Significant at $P < 10\%$ level, NS= Non-Significant

⇑Studied for 6 genotypes during 2001-2005 wheat growing seasons. Analysis was done using MSTATC version 1.42 using one factor RCBD model.

Appendix 6. Analysis of Variance (ANOVA) for testing the significant differences between biomass accumulation rates during sowing window 4 at various crop growth stages⍟

	At 3 leaf stage	*At anthesis stage*	*At maturity*
SS (replicates)	0.001	0.001	0.001
SS (genotypes)	0.030	4.500	83.215
SS (error)	0.007	0.008	0.002
MS (replicates)	0.001	0.001	0.001
MS (genotype)	0.006	0.900	16.643
MS (error)	0.001	0.001	0.001
F. value (replicates)	0.001 NS	0.023 NS	0.094 NS
F. value (genotypes)	8.897***	1107.508***	94205.246 ***

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level, * Significant at $P < 10\%$ level, NS= Non-Significant

⍟Studied for 6 genotypes during 2001-2005 wheat growing seasons. Analysis was done using MSTATC version 1.42 using one factor RCBD model.

Appendix 7. Analysis of Variance (ANOVA) for testing the significant differences between biomass accumulation rates across sowing windows at various crop growth stages♖

	At 3 leaf stage	*At anthesis stage*	*At maturity*
SS (replicates)	0.001	0.001	0.001
SS (genotypes)	0.087	8.095	22.507
SS (error)	0.005	0.002	0.008
MS (replicates)	0.001	0.001	0.001
MS (genotype)	0.017	1.619	4.501
MS (error)	0.001	0.001	0.001
F. value (replicates)	0.273 NS	0.539 NS	0.190 NS
F. value (genotypes)	31.564***	7472.567***	5697.884***

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level, * Significant at $P < 10\%$ level, NS= Non-Significant

♖Studied for 6 genotypes during 2001-2005 wheat growing seasons. Analysis was done using MSTATC version 1.42 using one factor RCBD model.

Appendix 8. Analysis of Variance (ANOVA) for testing the significant differences between means of various parameters⇧

	Days to Anthesis	*Days to Maturity*	*Plant Height*	*Biomass*	*Tillers*	*Spike length*	*No. of Spike lets*	*Grain Weight*	*Yield*
MS (SW)	3244	4993	13561	8261456	511817	7.74	59.0	462.7	900942
MS (genotypes)	1	0	59	64296	2881	1.52	2.5	18.1	7963
MS (years)	13	35	1003	812995	45767	0.93	10.3	181.3	117247
MS (replicates)	0	0	64	50392	16432	3.26	3.6	1.8	7980
MS (error)	5	1	61	36098	2798	0.51	1.6	6.8	5753
F. value (SW)	608.8***	3441***	222.37***	228.86***	182.95***	15.11***	37.35***	68.42***	156.59***
F. value (genotypes)	0.2 NS	0.0 NS	0.97 NS	1.781 NS	1.03 NS	2.96**	1.57 NS	2.67**	1.384 NS
F. value (years)	2.3*	24***	16.44 ***	22.522 ***	16.36***	1.82 NS	6.53***	26.81***	20.38***
F. value (replicates)	0.0 NS	0.0 NS	1.05 NS	1.396 NS	5.87*	3.26*	2.28 NS	0.26 NS	1.39 NS

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level, * Significant at $P < 10\%$ level, NS= Non-Significant

⇧Studied for 6 genotypes across 4 Sowing windows during 2001-2005 wheat growing seasons. Analysis was done using STATISTICA version 6.0.437.0 using Sigma-restricted parameterization and effective hypothesis decomposition.

Appendix 9. Means [a] and Standard Deviations (SD) [b] of various parameters⁂ in sowing window 1

PARAMETERS STUDIED	Wafaq-2001		Chakwal-97		NR-55		NR-232		NR-234		Margalla-99	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Anthesis *(Days after Sowing)*	115.0	0.0	115.1	0.1	115.1	0.1	114.5	1.2	115.2	0.1	115.6	0.9
Maturity *(Days after Sowing)*	158.3	0.5	158.4	0.4	158.5	0.4	158.2	0.2	158.2	0.1	158.0	0.5
Plant Height (cm)	109.6	1.6	109.8	1.9	110.6	2.6	112.2	4.8	108.7	1.2	111.8	3.7
Spike Length (cm)	10.0	0.8	10.9	0.5	10.5	0.4	10.8	0.4	10.9	0.6	10.5	0.7
No. of Spikelets (per spike)	19.4	1.3	20.3	1.1	19.6	1.0	20.0	1.4	20.0	1.4	20.5	2.1
No. of Tillers (per m^2)	354.7	34.9	375.0	23.8	332.7	44.6	318.7	36.9	336.9	15.6	373.4	41.2
Biomass (kg/ha)	14537.0	1292.7	15085.4	959.4	14505.1	1630.9	14698.8	1843.5	15016.9	1299.4	15132.7	961.1
1000 Grain Weight (gm)	41.0	1.5	39.1	1.9	41.1	3.2	42.0	3.0	41.1	2.1	40.4	1.9
Yield (kg/ha)	4638.5	595.6	4598.7	334.8	4296.0	970.2	4473.6	1101.9	4467.7	647.5	4469.1	499.5

[a] An informative and unbiased measure of the central tendency
[b] Commonly used measure of variation and dispersion
⁂ Studied for 6 genotypes during 2001-2005 wheat growing seasons.

Appendix 10. Means [a] and Standard Deviations (SD) [b] of various parameters ⇑ in sowing window 2

PARAMETERS	Wafaq-2001		Chakwal-97		NR-55		NR-232		NR-234		Margalla-99	
STUDIED	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Anthesis *(Days after Sowing)*	122.6	4.3	122.6	4.4	122.6	4.3	122.6	4.3	122.6	4.3	122.6	4.3
Maturity *(Days after Sowing)*	162.6	3.5	162.8	3.1	162.6	2.5	162.8	2.8	163.0	2.5	163.0	2.4
Plant Height (cm)	100.2	4.7	99.7	4.2	100.8	5.2	102.2	7.9	100.6	6.0	104.2	6.5
Spike Length (cm)	10.6	1.0	10.7	0.8	10.8	0.4	10.9	0.6	10.5	0.6	10.8	0.3
No. of Spikelets (per spike)	20.1	1.2	20.8	1.2	20.3	0.9	20.2	0.7	20.1	1.0	20.5	0.8
No. of Tillers (per m^2)	279.5	29.1	288.7	26.0	287.8	21.6	299.7	33.9	281.3	26.8	305.1	43.0
Biomass (kg/ha)	12270.8	1035.0	12579.2	804.0	12179.6	1584.1	12842.2	1756.4	12989.0	852.1	13322.0	746.6
1000 Grain Weight (gm)	37.8	1.6	38.9	1.7	39.7	4.3	39.4	1.9	38.9	1.9	36.7	5.1
Yield (kg/ha)	4404.9	561.9	4210.3	325.8	4027.1	398.5	4403.2	261.3	4055.4	755.8	4052.0	571.8

[a] An informative and unbiased measure of the central tendency
[b] Commonly used measure of variation and dispersion
⇑ Studied for 6 genotypes during 2001-2005 wheat growing seasons.

Appendix 11. Means [a] and Standard Deviations (SD) [b] of various parameters⊕ in sowing window 3

PARAMETERS STUDIED	Wafaq-2001		Chakwal-97		NR-55		NR-232		NR-234		Margalla-99	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Anthesis *(Days after Sowing)*	118.8	0.1	118.9	0.2	118.8	0.1	118.8	0.0	118.8	0.0	118.8	0.0
Maturity *(Days after Sowing)*	154.2	0.6	154.8	0.8	154.4	0.2	154.4	0.2	154.4	0.0	154.5	0.1
Plant Height (cm)	94.8	12.0	90.2	7.4	90.1	7.6	89.7	7.5	87.5	6.5	87.9	6.0
Spike Length (cm)	10.0	0.8	10.8	0.3	10.7	0.1	10.9	0.8	10.9	0.4	10.6	0.1
No. of Spikelets (per spike)	19.1	1.0	20.1	1.0	19.6	0.5	19.6	0.6	19.6	0.6	19.8	0.6
No. of Tillers (per m^2)	227.3	58.7	235.6	58.2	209.1	49.6	202.6	38.7	208.7	35.9	216.7	28.4
Biomass (kg/ha)	10340.3	1550.6	10198.3	1811.9	9614.6	1985.5	9611.6	1454.0	10346.4	1054.1	9557.0	1066.8
1000 Grain Weight (gm)	35.5	4.4	34.9	3.9	35.7	3.4	35.8	3.5	36.0	2.9	33.8	3.4
Yield (kg/ha)	3284.7	489.8	3019.9	640.4	2867.6	797.2	3036.9	821.9	3135.5	396.8	2597.8	773.8

[a] An informative and unbiased measure of the central tendency
[b] Commonly used measure of variation and dispersion
⊕ Studied for 6 genotypes during 2001-2005 wheat growing seasons.

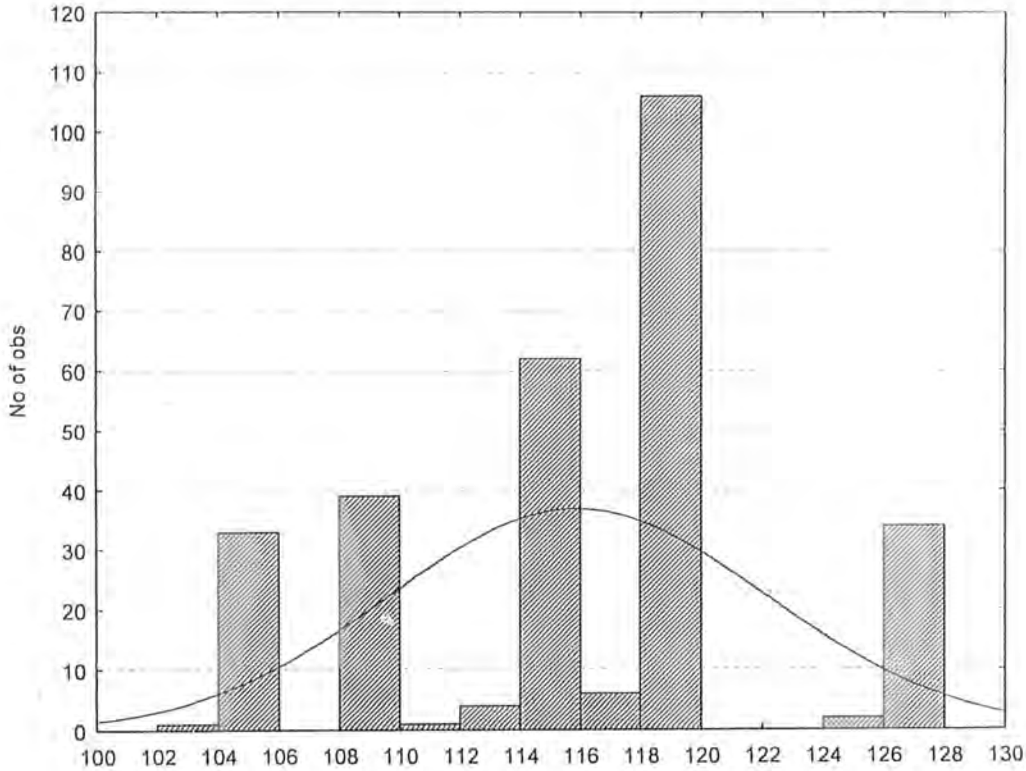
Appendix 12. Means [a] and Standard Deviations (SD) [b] of various parameters♜ in sowing window 4

PARAMETERS STUDIED	Wafaq-2001		Chakwal-97		NR-55		NR-232		NR-234		Margalla-99	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Anthesis *(Days after Sowing)*	106.6	2.9	106.8	2.7	106.8	2.7	106.7	2.8	106.7	2.8	107.6	2.3
Maturity *(Days after Sowing)*	143.4	0.3	143.2	0.1	143.3	0.0	143.3	0.1	143.3	0.1	143.4	0.2
Plant Height (cm)	77.6	12.9	73.5	12.4	76.7	15.3	79.0	15.9	83.9	14.7	82.1	13.0
Spike Length (cm)	9.9	0.4	9.9	0.8	10.0	0.6	10.0	0.9	10.2	0.6	10.1	0.6
No. of Spikelets (per spike)	18.1	1.1	18.0	2.3	18.1	1.7	18.1	2.1	18.5	1.9	18.5	1.5
No. of Tillers (per m^2)	150.2	84.7	120.7	69.4	146.4	88.4	165.9	67.8	181.1	92.4	169.6	87.9
Biomass (kg/ha)	6710.4	3468.8	5333.9	3054.8	6554.0	3762.0	7616.2	2966.1	8257.9	3671.9	7658.6	3623.2
1000 Grain Weight (gm)	35.9	1.2	35.4	2.5	35.7	2.1	36.1	0.8	36.1	1.4	36.1	1.0
Yield (kg/ha)	1992.8	1108.5	1574.7	1045.9	1885.5	1285.0	2250.1	989.5	2440.8	1245.4	2264.3	1276.4

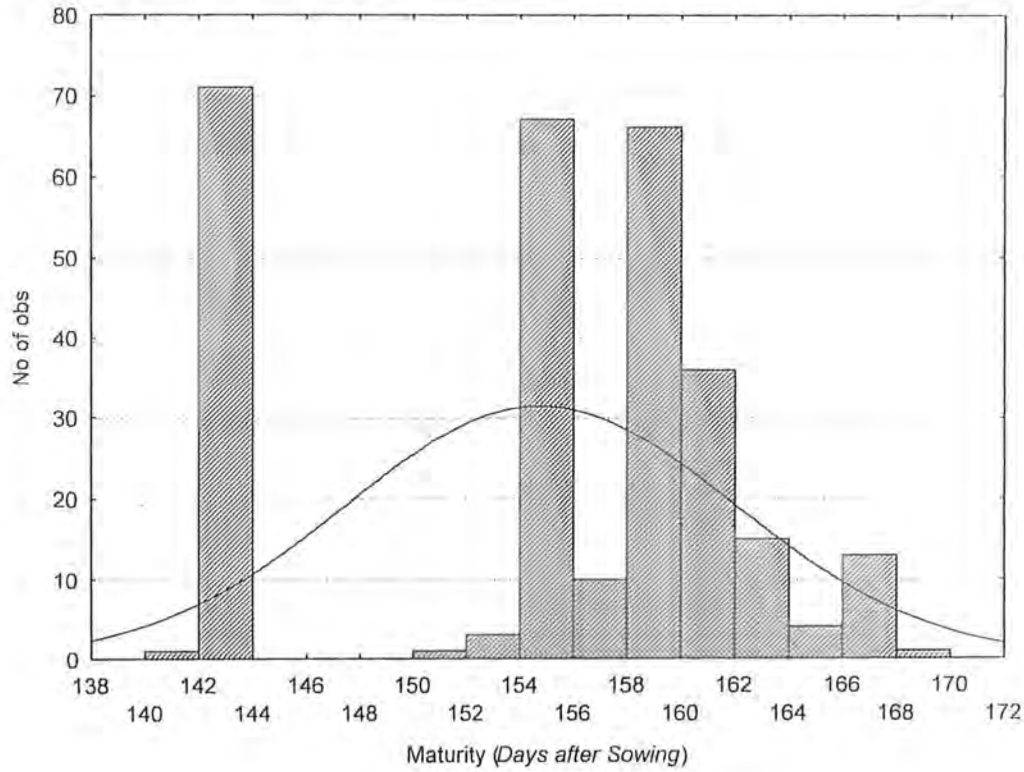
[a] An informative and unbiased measure of the central tendency
[b] Commonly used measure of variation and dispersion
♜ Studied for 6 genotypes during 2001-2005 wheat growing seasons.

Appendix 13. Aggregated crop growth rate in g/m^2/day of six genotypes in four sowing windows

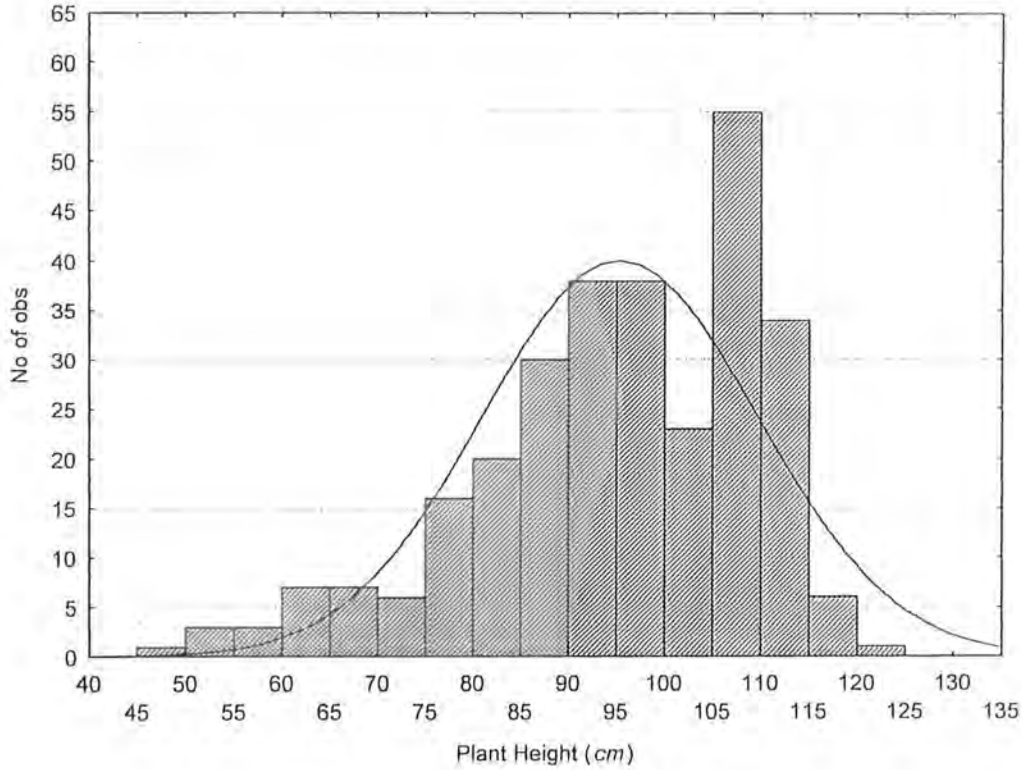
	SW1	*SW2*	*SW3*	*SW4*	*Average*
Wafaq-2001	7.7	7.8	8.1	4.7	7.1
Chakwal-97	8.4	7.9	7.5	3.7	6.9
NR-55	7.2	7.5	6.6	4.6	6.5
NR-232	8.2	8.2	6.1	5.3	7.0
NR-234	8.3	8.3	8.4	5.8	7.7
Margalla-99	8.4	8.5	6.1	5.4	7.1
Average	8.0	8.0	7.1	4.9	



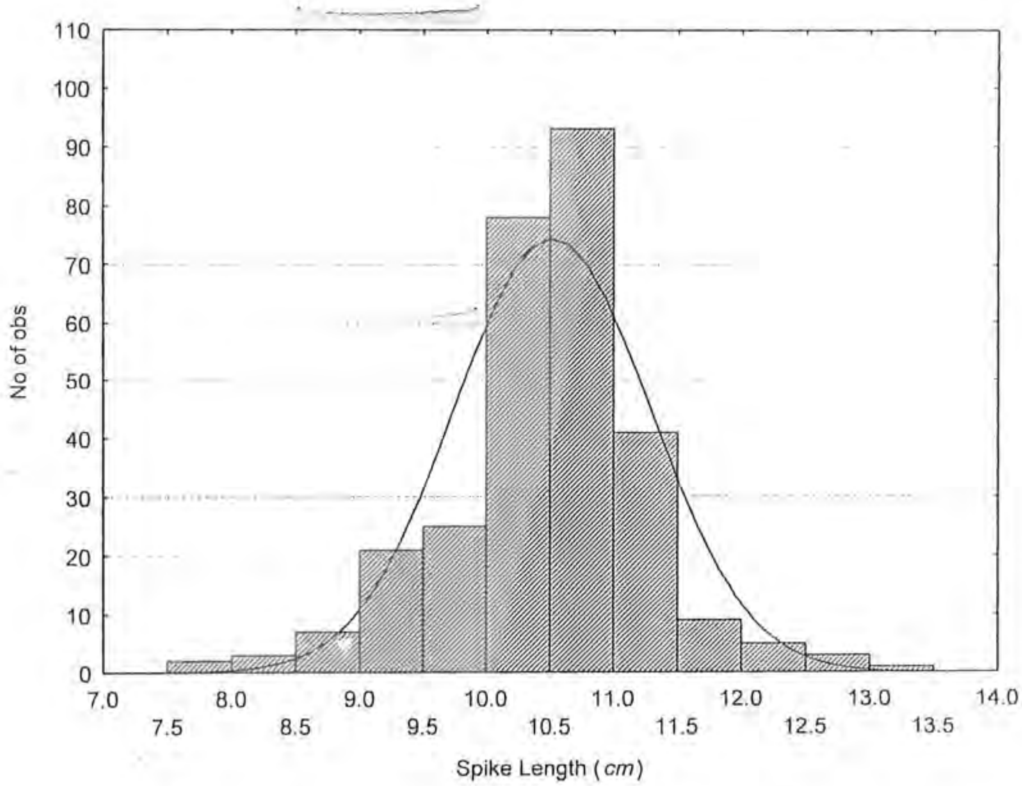
Appendix 14. Frequency distribution for anthesis (*Days after Sowing*). Observations were taken for six genotypes sown in four sowing windows during 2001-2005 wheat growing seasons. Curved line reflecting the expected normal.



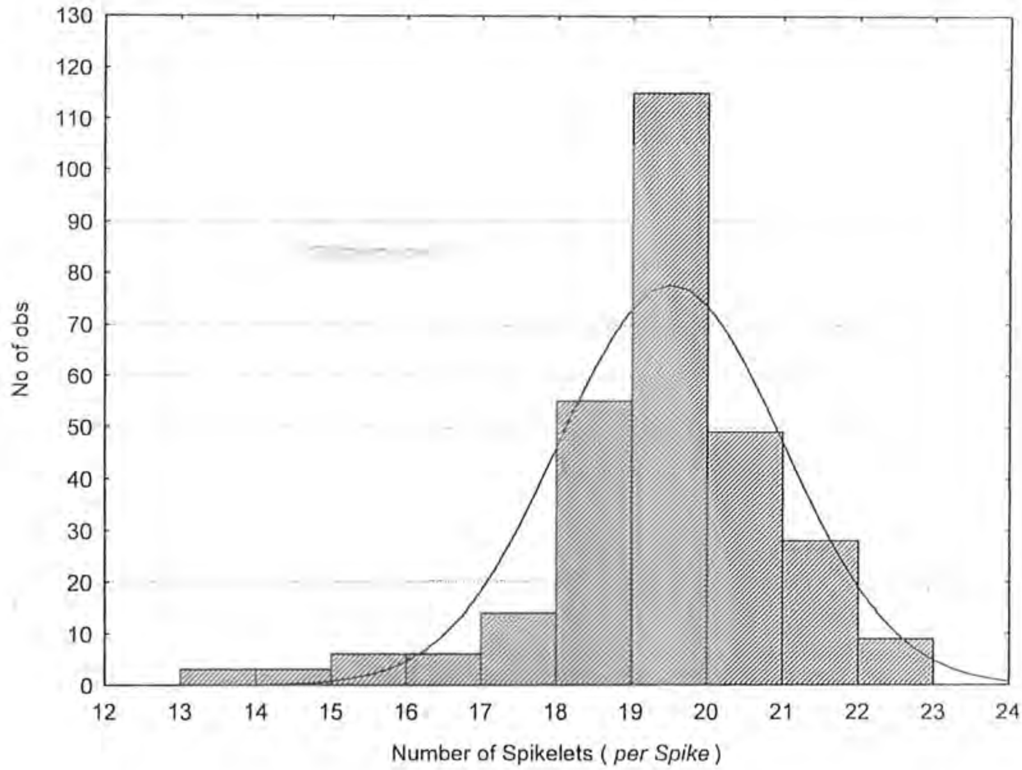
Appendix 15. Frequency distribution for maturity (*Days after Sowing*). Observations were taken for six genotypes sown in four sowing windows during 2001-2005 wheat growing seasons. Curved line reflecting the expected normal.



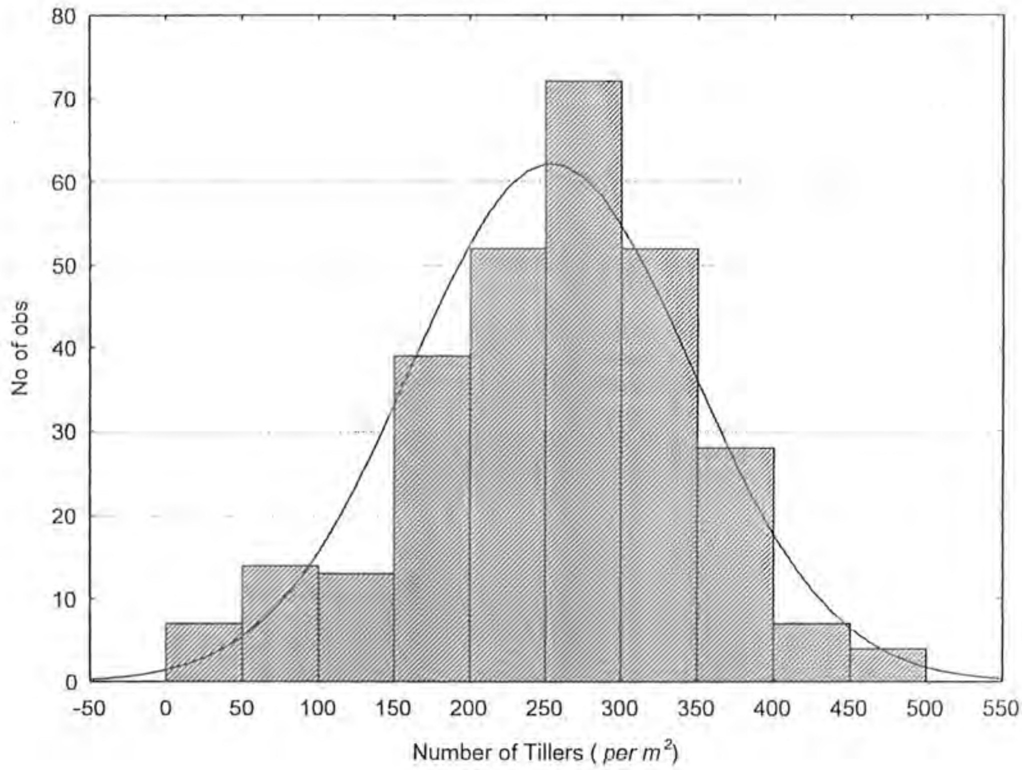
Appendix 16. Frequency distribution for plant height (*cm*) studied for six genotypes sown in four Sowing windows during 2001-2005 wheat growing seasons. Curved line reflecting the expected normal.



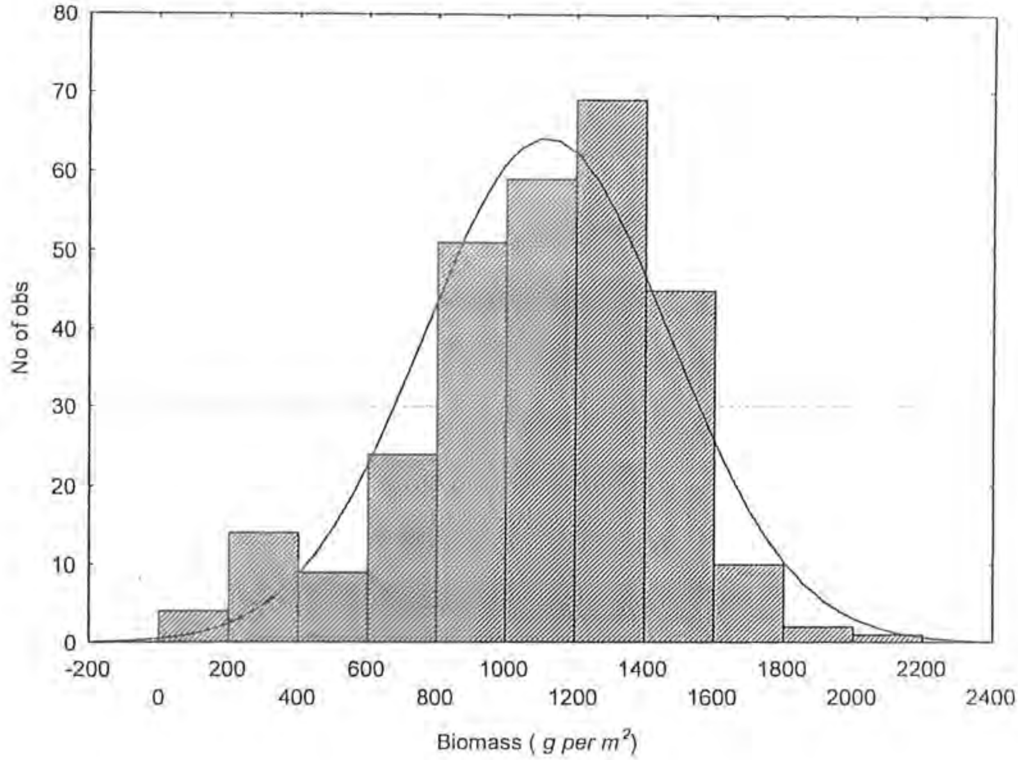
Appendix 17. Frequency distribution for spike length (*cm*). Observations were taken for six genotypes sown in four sowing windows during 2001-2005 wheat growing seasons. Curved line reflecting the expected normal.



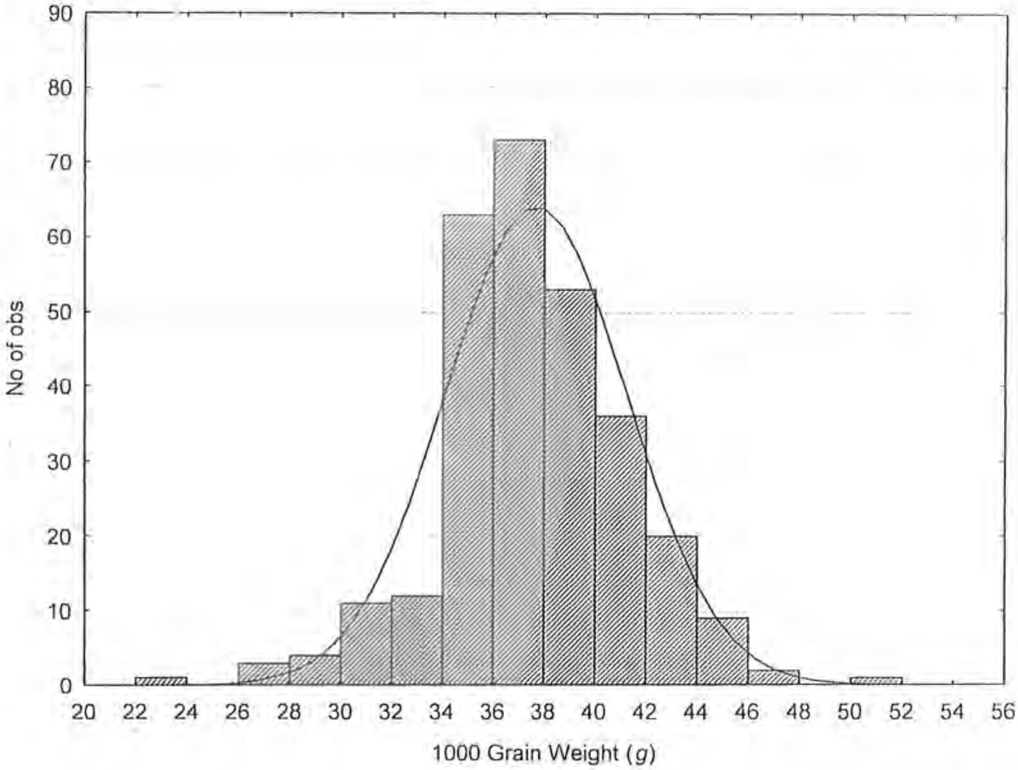
Appendix 18. Frequency distribution for number of spikelets (*per spike*). Observations were taken for six genotypes sown in four sowing windows during 2001-2005 wheat growing seasons. Curved line reflecting the expected normal.



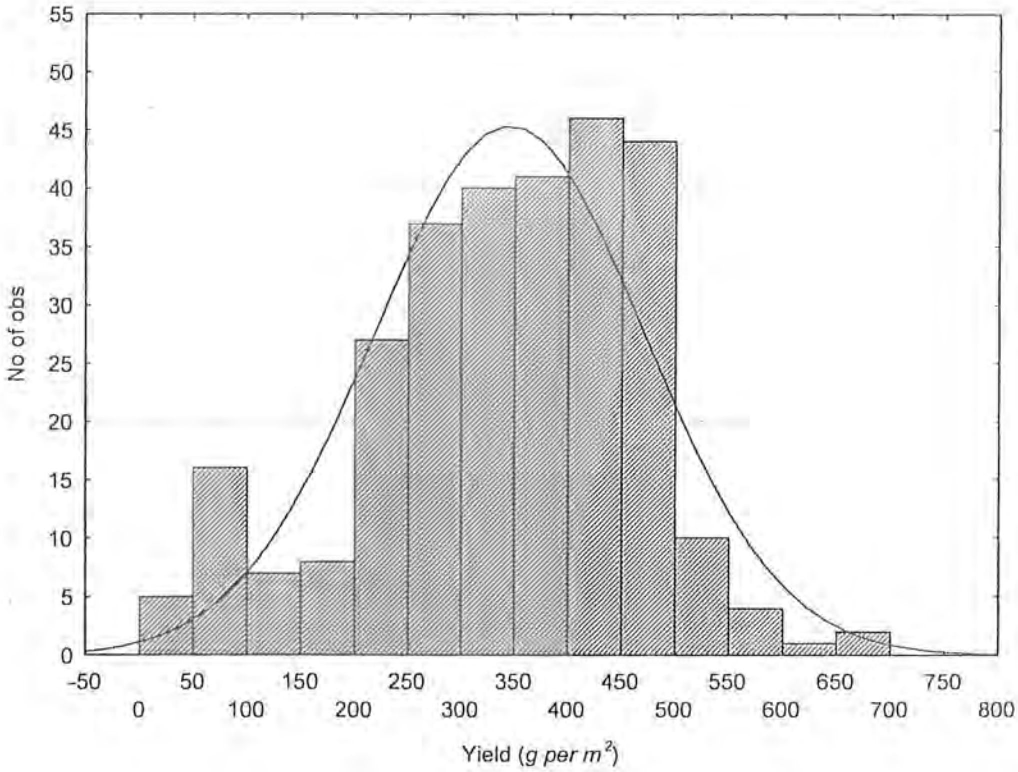
Appendix 19. Frequency distribution for number of tillers (*per m²*). Observations were taken for six genotypes sown in four sowing windows during 2001-2005 wheat growing seasons. Curved line reflecting the expected normal.



Appendix 20. Frequency distribution for biomass (*g per m²*). Observations were taken for six genotypes sown in four sowing windows during 2001-2005 wheat growing seasons. Curved line reflecting the expected normal.



Appendix 21. Frequency distribution for 1000 grain weight (*g*). Observations were taken for six genotypes sown in four sowing windows during 2001-2005 wheat growing seasons. Curved line reflecting the expected normal.



Appendix 22. Frequency distribution for yield (*g per m²*). Observations were taken for six genotypes sown in four sowing windows during 2001-2005 wheat growing seasons. Curved line reflecting the expected normal.

Appendix 23. Analysis of Variance on grain yield⍏ for six year (environments), four sowing windows (management) and six Genotypes and all possible interactions.

Source	*SS*	*MS*	*F*	*P*
Replication	15982.34	7991.17	3.45	NS
Management (M)				
Sowing windows	2702931.17	900977.06	388.74	***
Genotype (G)				
Cultivars/potential cultivars	39621.44	7924.29	3.42	***
G x M				
Cultivars/potential cultivars x Sowing windows	80415.33	5361.02	2.31	**
Error A	106612.83	2317.67		
Environment (E)				
Years	352222.14	117407.38	51.28	***
M x E				
Sowing windows x Years	517196.31	57466.26	25.10	***
G x E				
Cultivars/potential cultivars x Years	229924.36	15328.29	6.69	***
G x E x M				
Cultivars/potential cultivars x Years x Sowing windows	313389.19	6964.20	3.04	***
Error B	329727.50	2289.77		
Total	4688022.61			

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level,
* Significant at $P < 10\%$ level, NS Not Significant
⍏ Coefficient of Variation: 13.93 %

Appendix 24. Analysis of Variance on plant height⇑ for six year (environments), four sowing windows (management) and six Genotypes and all possible interactions.

Source	*SS*	*MS*	*F*	*P*
Replication	123.52	61.76	6.06	NS
Management (M)				
Sowing windows	40732.58	13577.53	1331.76	***
Genotype (G)				
Cultivars/potential cultivars	299.96	59.99	5.88	***
G x M				
Cultivars/potential cultivars x Sowing windows	1246.96	83.13	8.15	***
Error A	468.98	10.20		
Environment (E)				
Years	2954.36	984.79	97.83	***
M x E				
Sowing windows x Years	9423.67	1047.07	104.02	***
G x E				
Cultivars/potential cultivars x Years	1112.35	74.16	7.37	***
G x E x M				
Cultivars/potential cultivars x Years x Sowing windows	3011.62	66.92	6.65	***
Error B	1449.50	10.07		
Total	60823.50			

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level,
* Significant at $P < 10\%$ level, NS Not Significant
⇑ Coefficient of Variation: 3.34 %

Appendix 25. Analysis of Variance on spike length ⸸ for six year (environments), four sowing windows (management) and six Genotypes and all possible interactions.

Source	*SS*	*MS*	*F*	*P*
Replication	3.65	1.82	7.39	NS
Management (M)				
Sowing windows	23.18	7.73	31.30	***
Genotype (G)				
Cultivars/potential cultivars	6.62	1.32	5.36	***
G x M				
Cultivars/potential cultivars x Sowing windows	14.43	0.96	3.90	**
Error A	11.35	0.25		
Environment (E)				
Years	2.18	0.73	2.13	*
M x E				
Sowing windows x Years	36.73	4.08	11.99	***
G x E				
Cultivars/potential cultivars x Years	37.59	2.51	7.36	***
G x E x M				
Cultivars/potential cultivars x Years x Sowing windows	25.75	0.57	1.68	***
Error B	49.00	0.34		
Total	210.47			

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level,
* Significant at $P < 10\%$ level, NS Not Significant
⸸ Coefficient of Variation: 5.52 %

Appendix 26. Analysis of Variance on spikelets per spike⇮ for six year (environments), four sowing windows (management) and six Genotypes and all possible interactions.

Source	*SS*	*MS*	*F*	*P*
Replication	6.94	3.47	5.46	NS
Management (M)				
Sowing windows	168.25	56.08	88.26	***
Genotype (G)				
Cultivars/potential cultivars	12.12	2.42	3.82	***
G x M				
Cultivars/potential cultivars x Sowing windows	12.46	0.83	1.31	NS
Error A	29.23	0.64		
Environment (E)				
Years	31.92	10.64	14.85	***
M x E				
Sowing windows x Years	206.50	22.94	32.03	***
G x E				
Cultivars/potential cultivars x Years	60.96	4.06	5.67	***
G x E x M				
Cultivars/potential cultivars x Years x Sowing windows	46.46	1.03	1.44	*
Error B	103.17	0.72		
Total	678.00			

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level,
* Significant at $P < 10\%$ level, NS Not Significant
⇮ Coefficient of Variation: 4.34 %

Appendix 27. Analysis of Variance on tillers per m²₤ for six year (environments), four sowing windows (management) and six Genotypes and all possible interactions.

Source	*SS*	*MS*	*F*	*P*
Replication	32835.67	16417.84	12.79	NS
Management (M)				
Sowing windows	1536103.51	512034.51	398.84	***
Genotype (G)				
Cultivars/potential cultivars	14359.65	2871.93	2.24	*
G x M				
Cultivars/potential cultivars x Sowing windows	60094.49	4006.30	3.12	***
Error A	59055.33	1283.81		
Environment (E)				
Years	137308.40	45769.47	35.24	***
M x E				
Sowing windows x Years	264797.51	29421.95	22.65	***
G x E				
Cultivars/potential cultivars x Years	53954.43	3596.96	2.77	***
G x E x M				
Cultivars/potential cultivars x Years x Sowing windows	140854.65	3130.10	2.41	***
Error B	187043.00	1298.91		
Total	2486406.65			

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level,
* Significant at $P < 10\%$ level, NS Not Significant
₤ Coefficient of Variation: 14.25 %

Appendix 28. Analysis of Variance on biomass₶ for six year (environments), four sowing windows (management) and six Genotypes and all possible interactions.

Source	*SS*	*MS*	*F*	*P*
Replication	100810.55	50405.27	4.17	NS
Management (M)				
Sowing windows	24790231.01	8263410.34	683.46	***
Genotype (G)				
Cultivars/potential cultivars	321432.98	64286.60	5.32	***
G x M				
Cultivars/potential cultivars x Sowing windows	585923.34	39061.56	3.23	***
Error A	556166.28	12090.57		
Environment (E)				
Years	2436306.87	812102.29	66.54	***
M x E				
Sowing windows x Years	3882116.53	431346.28	35.34	***
G x E				
Cultivars/potential cultivars x Years	1045103.65	69673.58	5.71	***
G x E x M				
Cultivars/potential cultivars x Years x Sowing windows	2062746.20	45838.80	3.76	***
Error B	1757560.50	12205.28		
Total	37538397.91			

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level,
* Significant at $P < 10\%$ level, NS Not Significant
₶ Coefficient of Variation: 9.93 %

Appendix 29. Analysis of Variance on thousand grain weight⇧ for six year (environments), four sowing windows (management) and six Genotypes and all possible interactions.

Source	*SS*	*MS*	*F*	*P*
Replication	3.97	1.98	0.62	NS
Management (M)				
Sowing windows	1368.32	456.11	141.41	***
Genotype (G)				
Cultivars/potential cultivars	85.31	17.06	5.29	***
G x M				
Cultivars/potential cultivars x Sowing windows	89.71	5.98	1.85	*
Error A	148.37	3.22		
Environment (E)				
Years	564.93	188.31	53.84	***
M x E				
Sowing windows x Years	736.06	81.78	23.38	***
G x E				
Cultivars/potential cultivars x Years	146.76	9.78	2.80	***
G x E x M				
Cultivars/potential cultivars x Years x Sowing windows	266.84	5.93	1.70	***
Error B	503.67	3.50		
Total	3913.91			

*** Significant at $P < 1\%$ level, ** Significant at $P < 5\%$ level,
* Significant at $P < 10\%$ level, NS Not Significant
⇧ Coefficient of Variation: 4.96 %

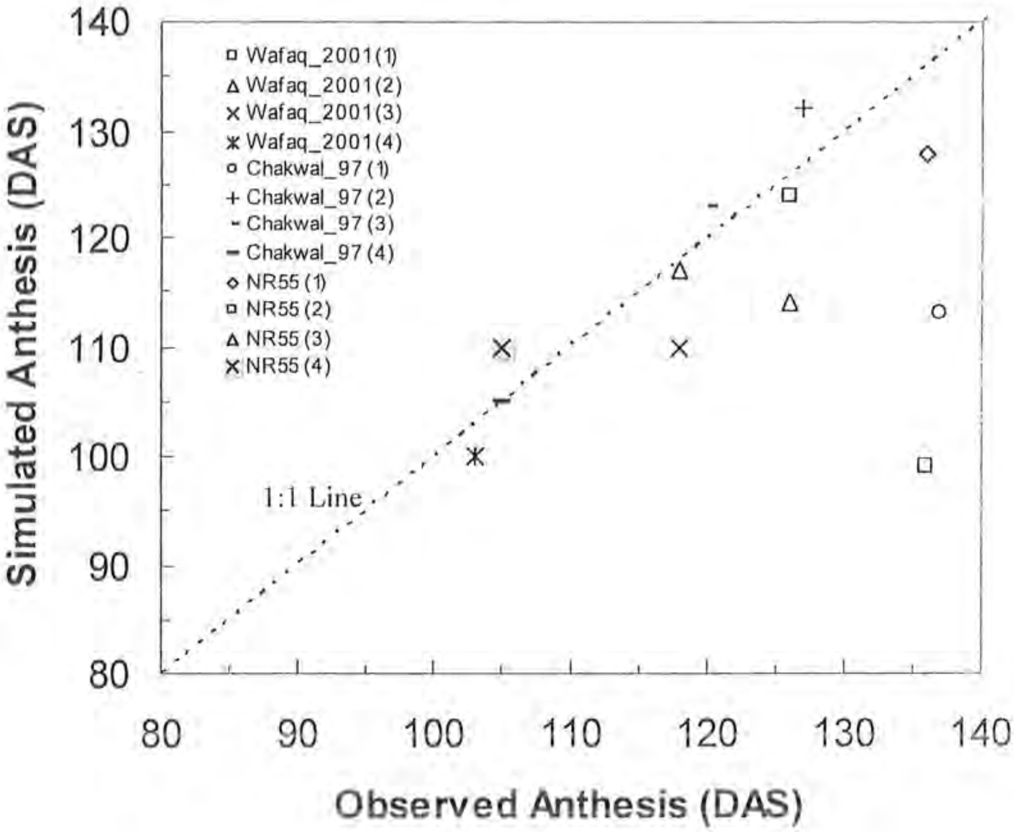
Appendix 30. Average grain yield, yield components, other agronomic traits related to crop growth and development, monthly total precipitation, mean monthly temperature, bright sunshine duration and daily solar radiations in each year⇮.

Variables‡	2001-02	2002-03	2003-04	2004-05	2005-06	2006-07
Average Yield						
Yield (*kg per ha*)	3188	3051	3550	3952	4046	3764
Yield components						
Spike Length (*cm*)	10	11	11	11	11	11
Spikelets (*per spike*)	19	20	19	19	20	20
1000 Grain Weight (*g*)	38	37	38	38	38	37
Agronomic Traits						
Anthesis (*Days after sowing*)	116	116	116	116	116	116
Maturity (*Days after sowing*)	155	155	155	155	155	115
Plant Height (*cm*)	96	93	95	96	95	97
Tillers (*per* m^2)	253	255	244	247	252	266
Biomass (*kg per ha*)	10965	10799	10713	11192	11653	11418
Precipitation (*mm*)						
P10	30	42.3	2.9	80.8	54.3	55.9
P11	7	17.8	17.3	19.8	6.3	14.2
P12	0.4	21.5	45	35.6	0	134.1
P01	0	39.3	91.2	39.3	63.2	0.5
P02	33.1	176.4	37	191.8	25.6	93.6
P03	43	82.8	0	79.4	45.5	143.2
P04	11.1	20.7	92.3	16.4	20.3	19.6
P05	2.9	22.8	12	30.5	62.9	79.6
Avg. Temperature (°*C*)						
T10	23.6	22.8	22	20.2	23.2	23.6
T11	17.2	16.5	15.9	16.2	16.3	16.8
T12	13.1	12.6	12.2	12.1	11.5	11.2
T01	10.1	10.9	11.2	9	11.1	10.4
T02	12.8	12.5	143	10.6	17.4	13.0
T03	19.1	17	21.2	16.8	18.8	16.1
T04	24.9	24.2	25.1	21.5	24	24.9

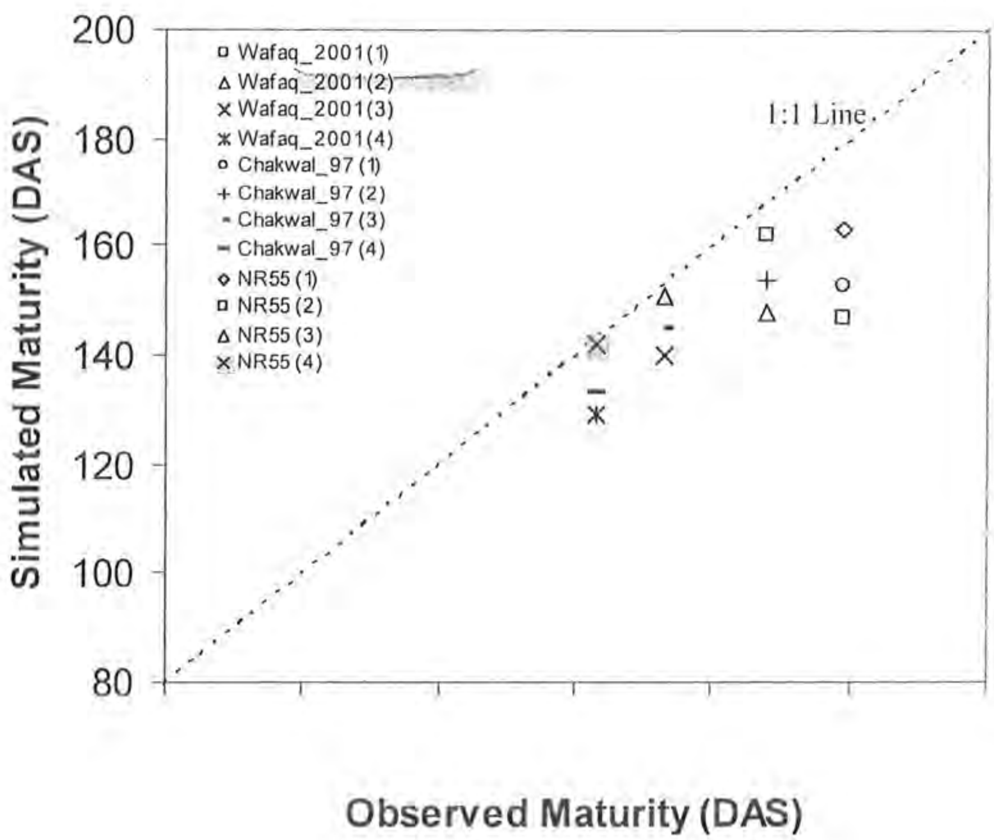
Variables‡	2001-02	2002-03	2003-04	2004-05	2005-06	2006-07
T05	30.6	27.8	28.2	25.3	31.1	28.6
Bright Sunshine Duration (*hrs*)						
SS10	254	253.5	302.7	228.7	283.6	273.5
SS11	235.3	247.9	221.3	216.9	245	192.3
SS12	190.5	191	193.3	177.11	236.5	181.0
SS01	195.7	205.7	147.4	175.2	161	246.0
SS02	164.6	155	244.2	105.3	162.4	139.2
SS03	242.7	217.3	303.5	181.0	218.7	230.8
SS04	245.4	266.4	236.1	252.4	291.2	321.6
SS05	309.6	322.3	249.5	294.8	333.2	307.5
Solar Radiation (*MJ/M2/Day*)						
SR10	16.3	16.31	18.1	15.26	17.35	16.93
SR11	13.29	13.70	12.77	12.66	13.59	11.82
SR12	8.99	8.9	8.98	8.4	10.14	8.64
SR01	9.71	9.99	8.36	9.17	8.72	11.15
SR02	11.02	10.69	13.59	8.9	11.02	10.14
SR03	16.43	15.82	19.13	14.8	15.82	16.32
SR04	19.5	20.36	18.47	19.67	21.38	22.78
SR05	23.39	23.96	25.1	22.63	22.63	23.28

P10-05 = total monthly precipitation for the months of October, November, December, January, February, March, April, May; T10-05 = mean monthly temperatures in October, November, December, January, February, March, April, May; SS10-05 = total sunshine duration for October, November, December, January, February, March, April, May; SR10-05 = daily solar radiation for October, November, December, January, February, March, April, May.

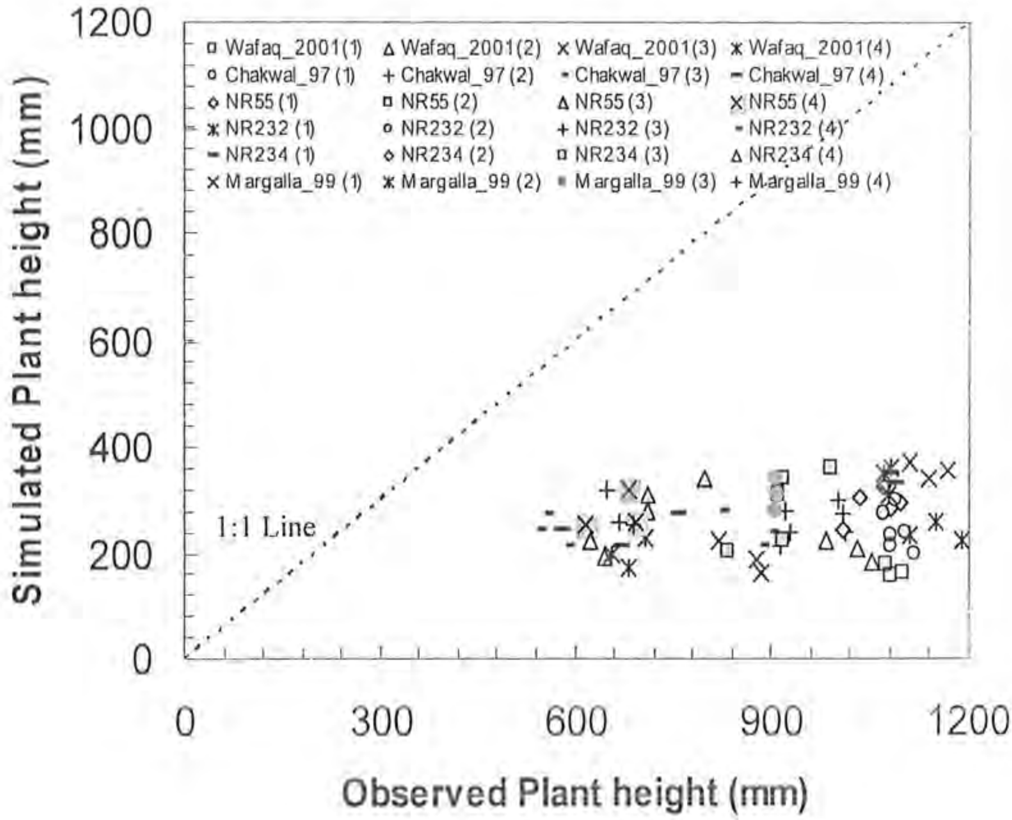
‡Yield, yield components and other agronomic traits averaged across all Sowing windows and genotypes.



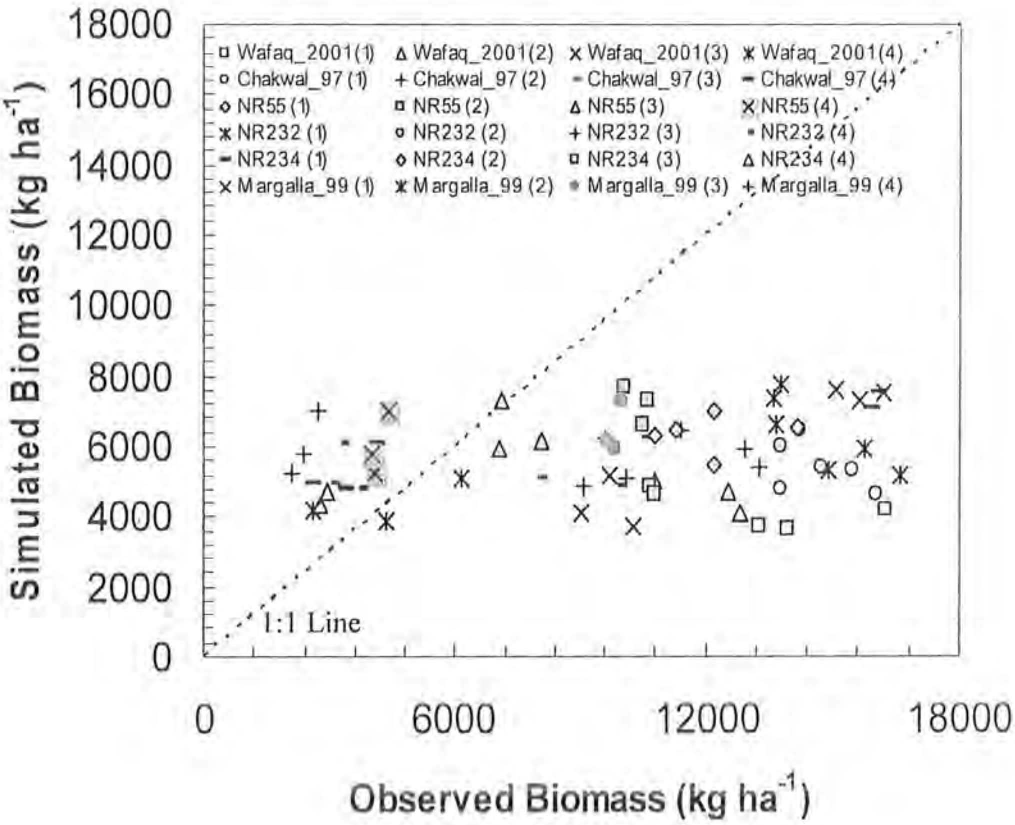
Appendix 31. Comparison of simulated and measured anthesis (*Days after Sowing*). Numbers 1, 2, 3 & 4 in parentheses with cultivar name indicate sowing window 1, 2, 3 and 4 respectively.



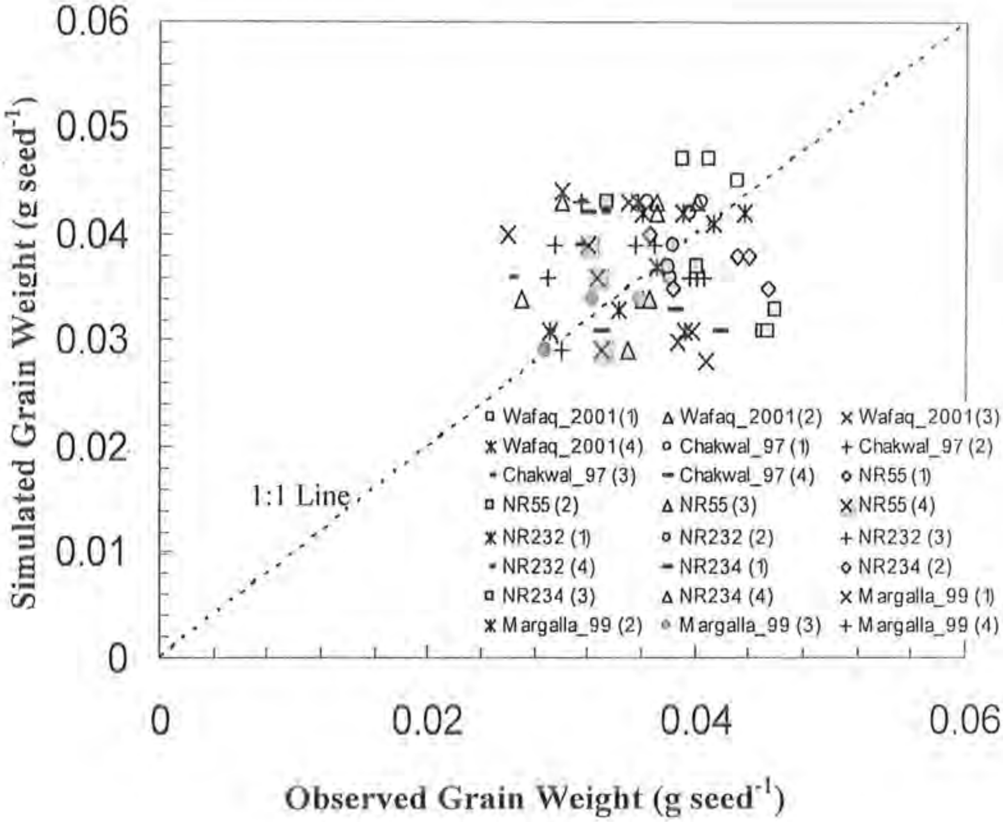
Appendix 32. Comparison of simulated and measured maturity (*Days after Sowing*). Numbers 1, 2, 3 & 4 in parentheses with cultivar name indicate sowing window 1, 2, 3 and 4 respectively.



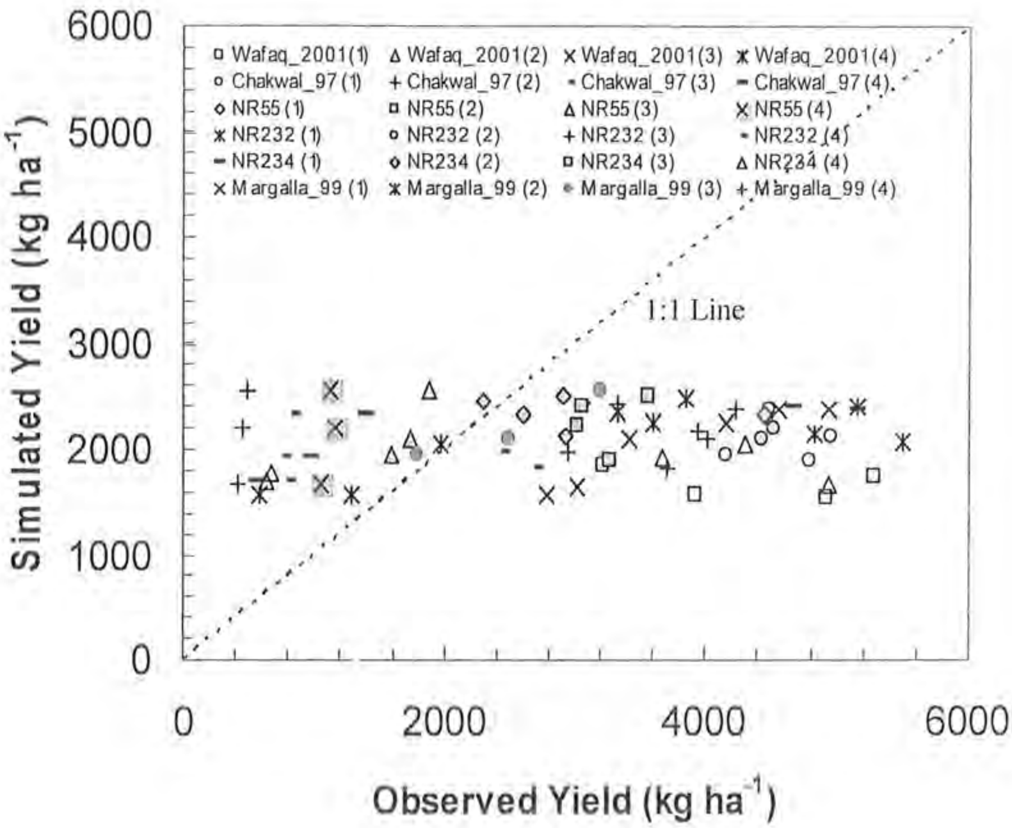
Appendix 33. Comparison of simulated and measured final plant height (mm). Numbers 1, 2, 3 & 4 in parentheses with cultivar name indicate sowing window 1, 2, 3 and 4 respectively.



Appendix 34. Comparison of simulated and measured biomass (kg ha^{-1}) accumulated at harvest stage. Numbers 1, 2, 3 & 4 in parentheses with cultivar name indicate sowing window 1, 2, 3 and 4 respectively.



Appendix 35. Comparison of simulated and measured grain weight (g seed^{-1}). Numbers 1, 2, 3 & 4 in parentheses with cultivar name indicate sowing window 1, 2, 3 and 4 respectively.



Appendix 36. Comparison of simulated and measured grain yield (kg ha^{-1}). Numbers 1, 2, 3 & 4 in parentheses with cultivar name indicate sowing window 1, 2, 3 and 4 respectively.

Appendix 37. Simulated and measured values regarding anthesis, maturity and plant height**

Cultivar / Advance Line	Measured		Simulated		Bias	*t*	Regression Equation	r^2
	Mean	SD	Mean	SD				
Anthesis (Days after Sowing)								
Wafaq-2001	116.75	7.80	116.75	8.22	0.00	0.00	S=1.049M-5.750	0.99
Chakwal-97	116.5	9.15	115.5	7.85	-1.00	-0.17	S=0.857M+15.709	0.99
NR-55	116.5	8.23	115.5	7.85	-1.00	-0.18	S=0.951M+4.7389	0.99
Maturity (Days after Sowing)								
Wafaq-2001	155.0	7.70	155.2	6.95	0.25	0.05	S=0.888M+17.67	0.97
Chakwal-97	153.2	7.30	151.5	7.85	-1.75	-0.33	S=1.061M-11.04	0.98
NR-55	153.0	7.87	151.5	7.85	-1.50	-0.27	S=0.968M+3.44	0.94
Plant height (mm)								
Wafaq-2001	991.08	109.6	993.0	117.1	1.92	0.04	S=1.03M-27.79	0.93
Chakwal-97	930.2	111.0	939.0	116.8	8.83	0.20	S=1.03M-23.04	0.96
NR-55	760.7	86.4	752.1	93.4	-8.58	-0.24	S=1.04M-42.06	0.93
NR-232	942.4	106.0	939.0	116.8	-3.41	-0.08	S=1.07M-67.92	0.93
NR-234	940.6	91.3	946.8	92.3	6.11	0.14	S=1.01M-05.95	0.94
Margalla-99	838.3	123.0	846.5	105.0	8.23	0.18	S=0.83M+150.6	0.94

* Means significantly different at $P < 5\%$ level

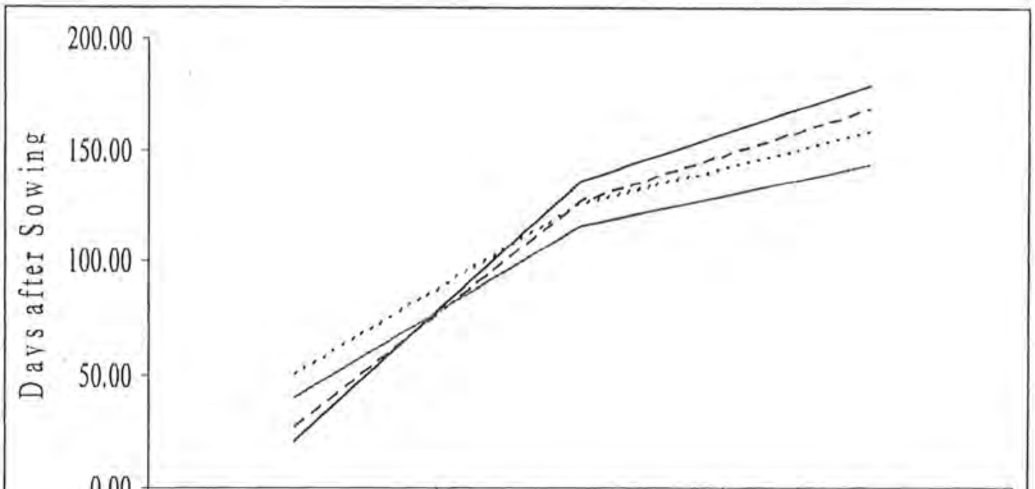
**Arithmetic means and standard deviation (SD), bias, t statistics, regression equations of simulated (S) and measured (M) values, and coefficient of determination (r^2) for anthesis, maturity (*Days after Sowing*) and plant height (*mm*) across Sowing windows 1, 2, 3 and 4.

Appendix 38. Simulated and measured values regarding biomass and grain weight**

Cultivar / Advance Line	Measured		Simulated		Bias	*t*	Regression Equation	r^2
	Mean	SD	Mean	SD				
Biomass (kg ha^{-1})								
Wafaq-2001	7002	833	6886	859	-115	-0.33	S=0.97M+120.03	0.88
Chakwal-97	6756	865	6615	868	-141	-0.40	S=0.89M+631.38	0.78
NR-55	6725	830	6615	868	-111	-0.32	S=0.90M+537.03	0.75
NR-232	6916	694	6644	871	-272	-0.84	S=1.11M-1044.3	0.78
NR-234	7097	576	6988	761	-109	-0.32	S=1.34M-2518	0.95
Margalla-99	6779	761	6683	870	-96	-0.29	S=1.06M-489	0.87
Grain weight (g $seed^{-1}$)								
Wafaq-2001	0.033	0.003	0.032	0.002	-0.001	-0.71	S=0.57M+0.01	0.58
Chakwal-97	0.036	0.003	0.037	0.003	0.001	0.55	S=0.58M+0.016	0.53
NR-55	0.041	0.003	0.040	0.004	-0.001	-0.76	S=0.95M+0.001	0.69
NR-232	0.036	0.003	0.035	0.003	-0.001	-1.22	S=0.83M+0.005	0.88
NR-234	0.035	0.004	0.034	0.003	-0.001	-0.74	S=0.68M+0.01	0.86
Margalla-99	0.033	0.003	0.032	0.003	-0.001	-0.92	S=0.71M+0.008	0.72

* Means significantly different at $P < 5\%$ level

**Arithmetic means and standard deviation (SD), bias, t statistics, regression equations of simulated (S) and measured (M) values, and coefficient of determination (r^2) for anthesis, maturity (*Days after Sowing*) and plant height (*mm*) across Sowing windows 1, 2, 3 and 4.



	3 leaf stage	Anthesis	Maturiy
PW1	21.00	136.00	179.00
PW2	27.00	126.00	168.00
PW3	50.00	125.00	158.00
PW4	39.00	115.00	143.00

Appendix 40. Duration of crop growth stages as affected by changing in sowing time