Mapping Simulated Bt Cotton Productivity in Punjab under Changing Climate Scenarios using Modeling and GIS Tools

BY

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Dedication

This humble effort is dedicated to The Noble Five in the Universe [Prophet MUHAMMAD (P.B.U.H), Hazrat ALI (R.A), Hazrat FATIMA (R.A), Imam HASSAN (R.A) and Imam HUSSAIN (R.A)]

&

My beloved mother,

affectionate father

and loving siblings

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MUHAMMAD NAVEED ARSHAD

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LIST OF ABBREVIATION AND SYMBOLS

ABBREVIATION	DESCRIPTION	UNITS
*	Significant at or below 5% ($P < 0.05$)	-
**	Significant at or below 1% ($P < 0.01$)	-
CGR	Crop growth rate	$g\ m^{-2}d^{-1}$
DAS	Days after sowing	Days
F_i	Fraction of intercepted radiation	-
K	Extinction coefficient for short wave radiation	-
HSD	Honnest significant difference	-
LAI	Leaf area index	m^{-2} / m^{-2}
NS	Non significant	-
PAR	Photosynthetically active radiation	MJm^{-2}
R	Coefficient of correlation	-
R^2	Percent variance accounted for coefficient of Regression	%
RUE	Radiation utilization efficiency	$g\ MJ^{-1}$
Sa	Accumulated intercepted PAR	MJm^{-2}
T	Temperature	°C
Tb	Base temperature	°C
TDM	Total dry matter	$kg\ ha^{-1}$
DSSAT	Decision Support System for Agro-Technology Transfer	-
GOT	Ginning out-turn	%
MPD	Mean percentage difference	%
CRS	Cotton Research Station	-
CCRI	Central Cotton Research Institute	-
RF	Rainfall	Mm
HI	Harvest Index	%
RMSE	Root Mean Square Error	-

Abstract

Cotton is very important cash crop of Pakistan and its yield and fiber quality is directly affected by future changing climate. Two-year experiment was conducted at Faisalabad, Sahiwal and Multan during summer season of 2014 and 2015 to estimate crop yield under changing climate scenarios and develop cotton productivity maps using modeling and GIS. The treatments were comprised of two sowing dates (1st May and 1st June), three cotton cultivars (FH-114, FH-142 and MNH-886) and three nitrogen rates (150, 200 and 250 kg ha^{-1}). Experiment was planned in randomized complete block design with split-split plot. Statistical analysis of agronomic data collected from two-year experiment confirmed that cultivars FH-142 and MNH-886 sown with 200 kg N ha^{-1} on 1st May performed well under Faisalabad, Sahiwal and Multan. Crop model Decision Support System for Agro-Technology Transfer (DSSAT) simulated crop phenology, seasonal crop biomass, leaf area dynamics and seed cotton yield. The observed data was used for calibration and evaluation of CROPGRO-Cotton Model. Model calibrated well with the best treatment (1st May sown crop with 200 kg N ha^{-1}) having Root Mean Square Error (RMSE) of 0.81 day, 407.28 kg ha^{-1}, 448.40 kg ha^{-1}, 0.23, 0 day for anthesis days, total dry matter, seed cotton yield, leaf area index and maturity days for cultivar FH-142, respectively. Simulation results from seasonal analysis depicted that under future climate, 16%, 34% and 45% yield loss at Faisalabad; 23%, 34% and 36% yield reduction at Sahiwal and 20%, 32% and 35% decrease in yield at Multan till end of early, mid and late century, respectively. Strategy analysis showed that timely sown cotton cultivar FH-142 at Faisalabad and Sahiwal and MNH-886 at Multan in month of May with 200 kg N ha^{-1} can be viable option to get maximum yield. Geographic Information System (GIS) maps of cotton productivity were generated by running model in R script with two methods. Spatial analysis with Weather generator showed that cotton yield will reduce in future all over Punjab and Dera Gazi Khan, Mianwali and Khushab districts have potential of higher seed cotton yield under 2°C rise in temperature in future. GIS maps with Metamodel showed similar results along with Sahiwal, Okara and Pakpatthan as potential districts for future cotton in Punjab. Crop Model and Geospatial maps based on simulation can be helpful tools to predict crop yield under future climate to develop site-specific adaptation strategies by adjustment of sowing dates and fertilizer with better management practices for different genotypes.

CHAPTER-1

INTRODUCTION

Most ancient and holistic occupation of mankind is agriculture. It contributes a lot to community development, shifting from simple cultivation to modern precision agriculture (Bongiovanni and Lowenberg-DeBoer, 2004; Perveen *et al*., 2013). Pakistan's economy relies heavily on the growth of the agricultural sector. Value addition in agriculture by cotton contribution is 7.1 percent and 1.5 percent of GDP (Govt. of Pakistan, 2015). Cotton is a major source of raw material to biggest textile industry of Pakistan. It is also rich source of edible oil (~24%) whereas more than 70% oil is being imported by country every year (Cetin and Bilgel, 2002). Being world's fourth biggest cotton producing country after China, India and United States, per hectare yield (560 kg) is comparatively much low. The reasons behind yield reduction are imbalance nutrient management of the crop, improper irrigation, heavy weed infestation and faulty pest control. Site specific sowing time directly relates with accumulation of heat unit. Cotton's indeterminate growth habit depicts that nutritional stress and imbalances affect vegetative as well as reproductive metabolism and ultimately limit yield of seed cotton as well as seed and fiber quality (Nuti *et al*., 2006; Rasul *et al.*, 2011).

Climate directly influences the agriculture crop production and any fluctuation in climate may affect crop yields and ultimately food and fiber supply. Weather significantly affects crop growth and yield and plays a vital role in crop establishment. All phenological stages of cotton crop are very sensitive to fluctuations in maximum and minimum temperature (Luo *et al*., 2014). Complete crop growing cycle is maintained by these fluctuations in daily temperature while cotton planting time directly regulates phenological development. Early sown cotton produces less amount of biomass and less seed cotton yield and also late sown cotton results in yield reduction due to short reproductive phase and conversion of assimilates from biomass to economic yield. Optimum planting time enhances process of biomass accumulation to complete growing cycle that ultimately leads to increased crop yield (Arshad *et al*., 2007; Conaty *et al*., 2012).

Climate smart, highly potential, high responsive to inputs and adaptive to various climate varieties of cotton crop are success keys to get maximum yield (Ali *et al*., 2005). In different cultivars yield is decreased due to less boll weight and numbers associated with less dry matter production. Some cultivars have their reduced leaf area index (LAI) due to inability of proper canopy development (Bange *et al*., 2003). It is also reported that cotton yield varies among different cultivars which convert radiant light to photosynthesis (Wajid *et al*., 2010). Some conventional cultivars are sown too early or too late by farmers in Pakistan and severely affected by heat stress. Many scientists documented cultivars that mature late also most vulnerable to square dropping and boll shedding when they are gown under higher day and night temperature. Being a thermal sensitive crop, there is dire need of some cultivars that can grow best in all situations. To get sustainable crop production, climate resilient cultivars can be one of the viable options under current and future climatic conditions (Kakani *et al*., 2005). On the other hand, suitable cultivars sown at optimum time can give significant production.

Enhancing nitrogen fertilization for different cotton cultivars is one promising way of adapting production practices to reach optimum economic returns (McConnell *et al*., 1993). Fiber strength and length of cotton are the two major fiber quality parameters. They link with the quality of both cotton bale and yarn (Bradow and Davidonis, 2000; Jost, 2005; Ge, 2007). Many factors are responsible for low cotton yield and poor fiber quality. The primary factors which effects the cotton fiber quality are genotype and nutrients and secondary factors are different agronomic practices such as sowing time, seed rate, method of irrigation and environmental conditions (Subhan *et al*., 2001). Cotton seed yield reduces due to high N availability which causes the shifting of balance between vegetative as well as reproductive growth by increasing vegetative growth (Howard *et al*., 2001).

Global circulation models are helpful to simulate mean rise in temperature and it was estimated that world temperature will rise from 2.8°C to 5.2°C (4°C average rise) and rainfall will be increased from 7.1% to 15.8% (10.1% average increase). Thirty years past weather data confirmed a warm climate of Pakistan in future with 0.1°C-0.2°C rise in temperature per ten years and variation in rainfall expected from 1.0% to 1.5% on an average of ten years was recorded for whole Pakistan areas (Allen, 2004; Rosenzweig and Hillel, 2015). Changing climatic scenario represents the present and future weather changes as well as climate trends. Their impact on crop production stimulate future research according to interest at public and policy level by analysis of agricultural productivity and climatic variation (Lansigan *et al*., 2000; IPCC, 2014). Variations in climatic events predominately affected agricultural crop production. Extreme weather directly influenced crop growth and developmental processes (Peng *et al*., 2008). Important growth stages of crop are more vulnerable to incidence of climatic extremes that reasonably reduce final crop yield (Tripathi and Vasan, 2014). Ultimately, it leads to a serious threat of crop production and climate variability develops a serious economic and social implications (Iqbal *et al.*, 2003; Ji *et al*, 2007). A clear understanding of the climatic impacts on crops and their vulnerability of agriculture production demands improve adaptive strategies to mitigate the negative impacts of climate change.

Decision-making tools for crop management are widely used for sustainable production under uncertain climatic conditions (Zingore *et al*., 2011). Model's simulations are viewed as influential tools for studying the impacts of various aspects on quality characters in cotton crop (Jamieson and Semenov, 2000; Rinaldi *et al*., 2003). Well Simulated and validated models take minimal time as compared to field experiment to evaluate impact of various agronomic management practices and a very helpful tool for risk management (Evett and Tolk, 2009). Simulation models can improve understanding of research problems and interaction of climatic, plant genetics, physiological variables of crop and assist and further broadening of research ideas (Harpal and Tupper, 2004). Models are key elements for assessment of agricultural management strategy to optimize crop yield (Boote *et al.*, 1996; Sinclair and Seligman, 2000). These assessments are based on variations in environmental conditions, mainly rise in CO_2 level, change in rainfall pattern, fluctuation in temperature and variation in radiation interception on crop could be probable reason that influence overall yield. Change in crop with respect to time are accurately estimated with the help of models (Hume and Callender, 1990). Computer based crop simulation models that depend on initial soil conditions and daily weather data can contribute in optimizing crop yield by the development of site-specific recommendations. Predictable crop growth models are necessarily required to carry out yield formation analysis without the limitation of qualitative and quantitative parameters mentioned above (Kakani *et al.*, 2005). Various research groups have conducted studies to evaluate climate change impacts on crop production using different crop growth models (Arshad, 2006). CROPGRO-Cotton under DSSAT can minimize risks associated with environmental variability and to efficiently utilize available resources (Boote *et al*., 2010; Hoogenboom *et al*., 2015). Scientific work on several mechanistic models were testified by scientists on yield and development of cotton to evaluate site specific environmental conditions of crop from planting to harvesting (Hima *et al.,* 2004). Integration of crop simulation modeling and geographic information system can be helpful for agro-climatic assessment and provide basis for crop management (Badini *et al*., 1997). This can also help in analysis of cultivars suitability.

A geographic information system (GIS) allows us to question, visualize, analyze and understand the data to disclose patterns, relationships and trends. GIS technology provide basis to geospatial analysis and digitizes the crop data. Geo-design combines geography and data with crop modeling, simulation, and visualization to results of any experiment (Perveen *et al*., 2013). ArcGIS platform proves vehicle for building thoughtful communities that faces these challenges. ArcGIS users can utilize any GIS resource such as maps, imagery and geodatabases (Pratt *et al*., 2012). Another platform is R that provide high level statistical computation and graphs (R Core Team, 2017). Use of novel technologies such as crop simulation modeling and GIS can overcome farmer's problems. To develop simulated cotton productivity obtained from simulation modeling, GIS technology provides a valuable set of tools that allow data transformation into more useful information for decision-making (Pollak and Corbett, 1993). This technology can be stretched on local scale in various regions of world for different crop types. In agro-climatic conditions of Pakistan, scientific studies on use of simulation models along with Geographic Information System for climate change impact assessment on cotton have not been investigated. A two-year experimental research was planned and implemented to fulfil below mentioned objectives:

1. To evaluate the impact of planting time, cultivar and nitrogen rates on seed cotton yield under varying environments of Punjab.
2. To ascertain the application of the dynamic CROPGRO-Cotton under DSSAT model for forecasting final crop biomass and cotton yield in context of future climate change.
3. To determine the ecologically and economically best management strategy for cotton using seasonal analysis tool under changing climate scenario.
4. Mapping of Bt cotton productivity to evaluate the spatial variability of crop yield under changing climate.

CHAPTER-2

REVIEW OF LITERATURE

Climate change is becoming a major challenge for future global food security. Climatic factors such as temperature, carbon dioxide concentration, precipitation and solar radiation has direct impact on growth and development of crop plants, individually or by interacting with other factors (Lansigan *et al*., 2000; Singh, 2005). Variation in cotton growth and yield variables among different locations are due to differences in environmental conditions (Gonias *et al*., 2012).

2.1. Effect of Sowing Dates on Cotton

The general observation about sowing date effect is that early sowing enhances seed cotton yield because cotton plant is of indeterminate habit hence early sown crop gets more growth period, increased canopy development, more leaf area index and leaf area duration (Gallagher and Biscoe, 1978; Reddy *et al*., 2005; Singh *et al*., 2007), more interception of photosynthetically active radiation (PAR) resulting greater total dry matter production, more fruit bearing branches, heavier and more mature bolls per plant and enhanced seed cotton yield. Early sown cotton can be helpful in better crop establishment and also reduces the drought and stress conditions for crop (Milford *et al*., 1985).

Early post emergent plants exposed to cooler nights (< 12°C) called cold shock have to face cold stress and it slows down the development rates. Similarly, if the night temperature is less than 20°C then it hinders the boll development (Bange and Milroy, 2004). Overall models are reliable tools, which are being used to evaluate the optimum sowing time for different cotton cultivars (Singh *et al*., 2007; Bange *et al*., 2008). Studies on the timings of phenological events, optimal conditions for each phenophase and connection with yield determinates are essential to boost cotton productivity for suitable sowing time and cultivars under fluctuating environmental conditions. Sowing of cotton at appropriate time provides maximum length of growing season which harvests peak solar radiation and accumulates more biomass (Arshad *et al*., 2007) while delayed sowing is exposed to high temperature at crop stand establishment stage and low mean temperature at reproductive stage (Akhtar *et al*., 2002). Cotton area in Pakistan is high temperature zone where summer temperature exceeds 45°C which may adversely affect cotton growth and development and ultimately seed cotton yield (Rehman *et* *al*., 2004). Physiological and metabolic processes of cotton have thermal range from 23°C to 32°C which is considered as optimal for growth and development (Pettigrew and Johnson, 2005; Conaty *et al*., 2012). Late Planting results in yield reduction due to short reproductive phase as compared to early planting. Early sown cotton produced more seed cotton yield due to higher boll retention while it could also reduce late season cold stress during reproductive phase by shifting it towards completion of its life cycle earlier (Akhtar *et al*., 2002). The objective of optimum sowing time is to overcome the cold shock and to reduce heat stress incidence to ensure that fruit has sufficient time to mature with better quality and optimum seed cotton yield (Singh *et al*., 2007). The cotton plant unlike rice and wheat processes more limitation of their agro-ecologic adaptability and this all depends on cropping season and weather conditions of that location (Ali *et al*., 2004). Although the cotton plant is a “sun-loving” plant, but an exceptionally higher temperature at reproductive phase higher than 36°C affects seed cotton yield significantly and it is considered as a critical factor for low productivity of cotton varieties grown under different climatic conditions of Pakistan (Arshad *et al*., 2003). Cotton plant shed about 65-70% fruiting points due to head induced sterility and humidity increase during monsoon. Cotton boll shedding starts when average daily temperature reaches 32°C or higher and 50% decline in yield and total shoot biomass was recorded when plants were exposed to growth under a 40°C day and 30°C night temperature comparative to plant grown under the optimal day and night temperature (30 and 20°C respectively) condition (Reddy *et al*., 1996).

Bauer and Roof (2004) conducted two years experiment to study the normal and late-planted cotton and possible impacts on different fiber quality parameters, especially those parameters which are directly related to the fiber secondary wall characteristics. In second year, canopy photosynthesis (due to rise in LAI) was 21% higher than the first year. Moreover, lint yield was also observed 22% greater in second year than in first year. However, harvestable product was reduced due to late sowing of crop (30% yield reduction).

Somoro *et al*. (2001) conducted series of experiments to assess the best planting date for cotton variety Marvi (CRIS 5A) whereas they documented that optimum planting time for cotton area in Sindh province of Pakistan is from 1st of May to 15th of May. Another experiment was conducted in Sindh province of Pakistan by Arain *et al*. (2001) to records seed cotton yield under different sowing dates and concluded that higher cotton production was achieved when crop was sown from 15th of April 15 to 1st May.

Pettigrew (2002) conducted an experiment on cotton and reported that shifting crop sowing time earlier in the earlier months of year basically escape late season insects and develop more under favorable weather conditions. He conducted a study of early planted cotton to analyze the growth, development and seed cotton yield that escape late season insects and develop more under more favorable weather pattern. Observations recorded were early season light interception, weekly blooms, early season dry matter partitioning, cotton lint yield and fiber quality. It was concluded that LAI was 172% higher than normal planted crop and for the early planted crop, it contributes to a 55% greater canopy light interception at that time. Mississippi delta cotton producers has opportunity from early Planted cotton that normal and lint yield will also rise in early planted cotton.

Muhammad *et al.* (2002) studied evaluation of optimum cotton growing period for different cultivars under sown in south part of Punjab. This experimental comprised of five planting dates starting from 1st of May till end of the month of June having fifteen days gap and cultivars (CIM-473, CIM-446, CIM-482). It was concluded that optimum period of crop sowing ranged from 1st May to starting date of June for all genotypes produced higher crop yield whereas seed cotton yield reduced meaningfully in 2nd week and 4th week of June.

Akhtar *et al.* (2002) conducted an experiment to evaluate performance of various planting time on six genotypes of cotton. Treatments were comprised of six genotypes sown at four planting time (1st May-16th June). Experimental results concluded that crop perform best it was sown on 16th of May under climatic conditions of Bahawalpur region.

Akhtar *et al.* (2002) studied the effects of different sowing dates on six cotton varieties. There are four planting dates (June 1 to June 16) using six cotton varieties and concluded that the best crop was made on May 16 in Bahawalpur (Pakistan).

Ali *et al*. (2004) conducted an experiment to evaluate effect of different sowing dates on seed cotton yield under climatic conditions of Vehari, Pakistan. He reported that early sowing achieved higher seed cotton yield than late sowing. Highest seed cotton yield of 2039 kg ha^{-1} was obtained on 15th of May followed by 1847 and 1669 kg ha^{-1} sown on 1st June and

13th June, respectively. Cultivar CIM-446 out-yielded all other cultivars. Another field experiment was conducted by Hussein (2005) at Cotton Research Station (CRS), Sahiwal to estimate growth, development and radiation use efficiency of cotton as affected under different sowing dates and nitrogen levels using cotton variety NAIB-111. Crop was sown on 20th May and 10th June with four nitrogen levels *viz*, 50, 100, 150 and 200 kg ha^{-1} and concluded that early sowing had significant effect on crop germination, plant height, number of bolls $plant^{-1}$, average boll weight, number of sympodial branches $plant^{-1}$, seed cotton yield kg ha^{-1}, total dry matter production, LAI, CGR and radiation use efficiency. Hence May, sowing gave much better results than June sowing under Sahiwal conditions.

Arshad *et al*. (2007) conducted a field trial at Post Graduate Agriculture Research Station (PARS) University of Agriculture, Faisalabad to study the growth, development and radiation use efficiency of the four cotton varieties with two sowing dates under the climatic conditions of Faisalabad and his experiment showed that cotton planted in 20th May produced 18% higher seed cotton yield. This was due to 10% increase in flowers production and open bolls were 23% more. Moreover, it was concluded that 13% less ginning out-turn (GOT) was recorded in 10th June cotton (late sowing).

2.2. Effect of Cotton Cultivars

Performance of cultivars varies based on their environmental conditions and genetic makeup by which they are adapted to different soil and environmental conditions. Cultivars have different levels of immunity to plant diseases and pathogens and show different growth and developmental pattern under specific environmental conditions and respond differently to applied inputs (Pettigrew, 2008). Promising high yielding Bt cultivars play a vital role in seed cotton production in Pakistan (Ehsan *et al*., 2008). Sustainable cotton production is important to with suitable combination of various agronomic management practices and sensible use of various inputs.

Sowing date is very crucial to obtain maximum potential of Bt cotton cultivar in Pakistan. Selection of a cultivar is a major factor of crop productivity in any cropping system and even most critical in specific sowing dates for sustainable crop production (Bourland, 2003). Cultivars respond to environmental conditions due to differences in length of growing season (Khan *et al*., 2007). Plant growth parameters regarding seed cotton yield, fiber quality (Aziz *et al*., 2011), number of bolls per unit area, lint percentage, ginning outturn (%), staple length (Ehsan *et al*., 2008) also differed significantly among Bt cotton cultivars. Sowing dates also cause variability in seed cotton yield of Bt genotypes (Buttar and Singh, 2006), Bt cultivars are considered as higher yield cultivars due to more resistance against insect, pest and disease and longer growing season as compared to conventional cultivars (Perlak *et al*., 2001).

Variations in temperature and other interrelated weather components as regulated by sowing time directly affect cotton growth and seed cotton yield. Photosynthesis process in crop highly affected by these extremes that ultimately have a negative impact on leaf area index (LAI) and crop growth rate (CGR) (Reddy *et al*., 2005; Singh *et al*., 2007). Leaf area index is one of the important growth component that contribute to seed cotton yield. Similarly, higher growth rate of crop significantly affected during crop anthesis stage if crop was planted late in season. This is due to higher temperatures reducing duration of dry matter accumulation and prolonging crop development processes. Higher temperature also shortened duration of boll maturation that ultimately result in lower crop yield due to smaller boll size (Pettigrew and Johnson, 2005; Reddy *et al*., 2005). Higher day and night temperature induce harmful effects on crop growth and yield. Environmental stresses caused by higher temperature is one of the reason for yield variability among seasons (Lewis *et al*., 2000; Brown *et al*., 2003). Short duration cotton genotypes have more potential to accumulate more dry weight as compared to genotypes having longer duration. This is due to early crop canopy development along-with higher radiation utilization efficiency and more interception of light on crop (Bange and Milroy, 2000).

Ali *et al.* (2004) studied cotton yield of various cultivars under early, mid and late sown cotton as influenced by climate. Experimental results depicted that higher seed cotton was achieved in early sown crop in the month of May with Cultivar CIM-446 and reduction in yield was observed in late sown crop in the month of June as compared to other cultivars He concluded that cultivars performed differently under different sowing dates. Cheema (2006) conducted an experiment under Bahawalpur conditions to study growth and lint yield of cotton cultivars applied with different rates of nitrogen fertilizer. He noted that cultivar NIAB-111 attained maximum leaf area index and dry matter accumulation. However, maximum seed cotton yield was achieved by CIM-506 which was statistically at par with CIM-496. On the other hand, less production of cotton yield was recorded from cultivar NIAB-111 under agro-climatic conditions of Bahawalpur. Arshad (2006) conducted studies on growth, development and radiation use efficiency of four cotton varieties with two sowing dates under the climatic conditions of Faisalabad and documented that maximum seed cotton of (1463 kg ha^{-1}) was produced by SLH-284 followed by NIAB-111 (1347 kg ha^{-1}), CIM-496 (1183 kg ha^{-1}) and CIM-506 (1177 kg ha^{-1}), respectively. He documented that higher performance of crop can be attained in a condition when crop was sown on 20^{th} May and crop yield was higher.

2.3 Effect of Nitrogen Rates on Cotton

Nitrogen is one of major essential nutrients for plant growth along-with phosphorus and potash. It is part of cell organelle, proteins and chlorophyll; consequently, a deficiency in its supply has profound effect on growth and seed cotton yield. Nitrogen fertilizer influences cotton in a number of ways. Cotton yield can be improved by good management practices such a maintaining fertilizer (nitrogen) levels (Ali *et al*., 2001). For the production of cotton, the nutrient which is needed most regularly is nitrogen. Nitrogen application influences the development of the individual plant stand with important implications for the components of seed cotton yield. The quantity and quality of harvested seed cotton is determined by fertilizer application. Because cotton has indeterminate growth habit, hence increased nitrogen supply is essential for better plant growth and development of time to time new sprouting throughout crop duration (Hou *et al*., 2007).

Fritschi *et al*. (2003) conducted a study about effect of different nitrogen rates on lint yield of modern cotton cultivars that were Pima cotton (*Gossypium barbadence* L.) and Acala cotton (*Gossypium hirsutum* L.) Experiment was designed with all other optimum management practices to develop an optimize nitrogen use strategy to get higher crop yield. Treatments include control plots (zero nitrogen) along with 56, 112, 168 and 224 kg ha^{-1} nitrogen levels plots. For estimation of nitrogen utilization, shoot samples were collected at different growth stages of crop, that were fractioned in to different components. At various development stages of cotton, nitrogen concentrations in Pima and Acala plant tissues were significantly affected by nitrogen treatment.

Iqbal *et al.* (2003) studied cotton growth, development and final yield influenced by various factors including environment and crop management and their impact of crop maturity. Three cultivars (MNH-554, MNH-552, AC-134) fertilized with five various doses of nitrogen (0, 75, 125, 175, 250 kg ha^{-1}) were evaluated. Observed data depicted that nitrogen applied with a rate greater than 175 kg ha^{-1} have no obvious effect of anthesis time. No significant effects were recorded at higher doses of nitrogen 250 kg ha^{-1} (1666 kg ha^{-1} seed cotton yield) and 175 kg ha^{-1} (1638 kg ha^{-1} seed cotton yield).

Another experiment was planned to investigate impact of planting date, density, and nitrogen fertilizer applied on total number of boll formed and final harvest yield of hybrid variety of Zheza 166 (Wang *et al*., 2008). They found that more total number of bolls was formed on sympodial branches of plants when crop was planted on mid of April and appropriate planting density (45,000 plants ha^{-1}) along-with recommended nitrogen dose (180 kg ha^{-1}). They were of the view that the highest boll number was obtained in plants sown on April 15 and in order to get the highest lint cotton yield and lint index, the optimum plant density and nitrogen level were 45000 plants ha^{-1} and 180 kg N ha^{-1}, respectively.

Carbon dioxide and nitrogen interactively influence on growth, development, fiber quality and seed cotton yield of crop (Reddy *et al*., 2004). Elevated CO_2 concentration drastically affect quality of cotton fiber and under optimum nitrogen level, it will not have any visible effect on quality. Different levels of nitrogen significantly affect crop; however, Boquet (2005) under observed no significant difference irrigated and rainfed conditions. Hutmacher *et al*. (2004) documented that increase in lint yield of various cotton cultivars regulated by increase in nitrogen dose to an extent of 41%.

Wiatrak *et al*. (2005) tested the effect of N application on growth and yield of cotton with four nitrogen doses (0, 67, 134, 201 kg ha^{-1}) on crop growth, development and yield. It was concluded that seed cotton yield, total number of bolls formed and plant height increased with higher level of nitrogen. They declared that a nitrogen dose of one kg per hectare used enhanced cotton yield up to 1.74 and 2.76 kg per hectare in 1996 and 1997, respectively.

Nitrogen rates and sowing dates interactively affect seed cotton yield as reported by Toscano *et al*. (2005). The cotton sown earlier in April and late in the month of June were fertilized with different doses of nitrogen. Higher dose of nitrogen enhanced crop yield when crop was sown earlier than optimum time in the month of April whereas no obvious effect was recorded where crop was sown late in the month of June. Different cultivars of cotton respond different to various levels of nitrogen fertilizer. Cheema (2006) concluded that higher dose of nitrogen promoted higher cotton yield as compared to lower dose of nitrogen. Hussein (2006) also reported that the entire yield components including boll weight, number of mature bolls and cotton yield improved with increasing nitrogen dose. A higher dose of nitrogen produced more crop yield.

Boquet (2005) studied ultra-narrow row (UNR) cotton with wide spread cotton under rainfed and irrigated conditions along with different nitrogen rates (90, 112, 134 and 157 kg N ha^{-1}) and found that wide row planted gave 1096 kg ha^{-1} which is higher lint yield than UNR having yield of 771 kg ha^{-1}. Different nitrogen rates have no significant effects on both irrigated and rain-fed conditions.

Clawson *et al.* (2006) studied the impact of row spacing and N doses on cotton yield and yield components. Nitrogen rates were 0, 50, 101 and 151 kg N ha^{-1} and row spacing was 19, 38 and 76 cm (conventional row spacing). It was observed from data that plant height, boll weight and number of nodes on stem per plant decrease with decreasing row spacing. Plots having higher dose of N significantly influenced plant height, number of notes on stem per plant as well as average boll weight. Significant rise in crop yield occurred with the higher nitrogen levels.

2.4 Growth and Radiation Use Efficiency

The significance of leaf area as determinant of radiation interception has long been well recognized and appreciated. Main inputs that affect leaf area per plant and which grower can control are nitrogen and suitable cultivar. The principal means for increasing TDM include, optimizing the assimilate area i.e. leaf area index (LAI) and leaf area duration (LAD) to enhance the interception of photosynthetically active radiation (PAR), improving the radiation use efficiency and redistribution of photosynthates in order to maximize economic yield. TDM of a crop is proportional to the total amount of intercepted radiation, which is itself largely determined by the size of leaf area and its distribution with time (Gallagher and Biscoe, 1978).

Early canopy development of cotton reduces its plant height and branches and thus lowers the overall vegetative growth of the cotton plant but increase light availability at the medium and the upper part of the canopy (Flower, 2002). Pettigrew (2002) testified that any shift in crop growing season i.e. early sowing of crop in the start of year might permit crop to grow fully and develop more under more favorable and optimum weather conditions and also to avoid heat stress and escape from insects of late season. Researchers worked on effect of early planting on growth, development, and yield and fiber quality of cotton. Experimental results depicted that early season light interception, dry matter partitioning, lint yield, yield components, weekly bloom count and fiber quality collected from cultivars sown earlier (first week of April) and normal sown showed a significant difference. Early sown cotton attained 172% more LAI that crop plants sown in normal planting that ultimately enhanced canopy light interception 55% greater than normal planting.

Photosynthesis in leaf affected by light intensity along with nitrogen contents in leaf as concluded by Milroy and Bange (2003). Radiation is very important for plant photosynthesis and cotton plant is very efficient in utilization of radiation into dry matter production. Crop canopy is also very important in capturing light. Radiation use efficiency relates with the genotype of cotton cultivar and nitrogen fertilizer applied to the crop plant. According to Ahmed (2003), cotton growth, yield and radiation use efficiency of various cultivars are significantly different.

Hussein (2006) reported that crop sown earlier attained higher leaf area index and its net assimilation rate and crop growth rate were also higher at Sahiwal than late sown crop and that correlated with higher dose of nitrogen. Cumulative intercepted radiations and light utilization efficiency were higher in early sown crop. All these contributed to maximize seed cotton yield in early sown crop than late sown. Cheema (2006) concluded that best response of NIAB-111 was observed with higher dose of nitrogen for all growth and radiation interception parameters. Arshad (2006) reported that May sown cotton at Faisalabad produced maxima in crop growth rate, leaf area index and accumulated radiation that contributed to a higher seed cotton yield with cultivar SLH-284 under Faisalabad condition.

2.5 Crop Growth Modeling

Different environmental and cultivar-specific factors affect dynamic processes of crop plant. Agronomic research has focused on formalizing and summarizing knowledge on growth and yield of field crops including cotton. For better utilization of available resources and sustainable crop production, crop management decision making is a very crucial factor which provides information needed to fulfil food and fiber demands of nation and to cope with uncertain climatic events and its pressure on water, soil and other relevant natural resources (Zingore *et al*., 2011).

When mathematical principles are combined to be presented as cause-effect process, the relationship can be referred as a mechanistic model. Agronomic research based on spatial and temporal attributes are resource intensive for a particular location of experiment conducted during a specific crop growth season and challenging as well. There is dire need of decision support system for tactical and sustainable crop production based on scientific knowledge to test improved site-specific crop management. Crop models are extensively used by researchers and policy makers in decision support for enhancement in crop efficiency (Jones *et al*., 2003). This can help to evaluate the impact of climatic variabilities, various management practices of crop including sowing dates, nitrogen fertilizer efficiency and adaptation of different genotypes under specific environmental conditions (Boote *et al*., 2010; Thorp *et al*., 2014a). Crop models take less time than long duration field experiments. Hence, farmers and, in particular, researchers can witness the possible impact of various management strategies on crop yield and accordingly they can change their management practices within time before achieving final crop outcome despite of long-term studies with more utilization of resources on their farms (Bannayan *et al*., 2004; Evett and Tolk, 2009). Crop simulation models support in selection of ideotypes that can perform best under particular environmental conditions and are well adapted to those conditions and models can also broad the vision to understand interactions between management practices, environmental conditions and cultivars as described by Yin *et al*. (2004).

Decision Support System for Agro-Technology Transfer (DSSAT) belongs to family of crop simulation models that have capabilities to examine crop management, cultivars, sowing dates, fertilizer management and climate impacts on cotton production (Thorp *et al*., 2014b). CSM-CROPGRO-Cotton in DSSAT as described by Hoogenboom *et al*. (2015) can be helpful tool (when calibrated and validated properly) in minimizing environmental risks due to huge variability and provide directions to cotton growers to make crop management decisions with optimized use of scarcely available crop resources (Boote *et al*., 2010). This tool allows researchers to test hypotheses and conduct series of virtual experiments related to crop growth under different environments that could possibly take years under actual field conditions (Farage *et al*., 2007; Malone *et al*., 2007). It allows stakeholders to combine scientific knowledge regarding growth, development and crop phenology that ultimately contribute to production by considering economic parameters as well for estimation of environmental impact. Such type of scientific knowledge will facilitate farmers in terms of growth and yield analysis and environmental risk assessment (Jones *et al*., 2003; Keating *et al*., 2003; Luo *et al*., 2010).

CROPGRO-Cotton model was tested for assessment of cotton phenology, growth and seed cotton yield of various cultivars (CIM-496, CIM-506, NIAB-111 and SLH-284) for different sowing dates (20^{th} May and 10^{th} June) and nitrogen doses (50, 100, 150 and 200 kg N ha^{-1}) and model predict well for both sowing dates (Wajid *et al*., 2014). Impact of changing environmental factors on sowing dates of cotton was evaluated under climatic conditions of Georgia and model performed well (Paz *et al*., 2012). CSM-CROPGRO-Cotton model under DSSAT proved a helpful tool for yield improvement and sustainable cotton production for development of agronomic management strategies (Pathak *et al*., 2007). These agronomic management strategies can be one option to reduce various environmental risks. Alternative crop management adaptations practices assessed with the support of model for improve crop production (Cavero *et al*., 2000). Farre *et al*. (2002) tested various sowing dates with the help of model for adaptation in Australia and also tested canola. Kumar *et al*. (2002) used CROPGRO Soybean model v3.0 to determine optimum sowing dates across the globe for various crops, especially for soybean in India (Mall *et al*., 2004). Cotton sowing date with model evaluation and applications at broad range of temporal variation for cotton cultivars in Pakistan are still unavailable.

Another major step for simulation of crop modeling is parameterization of model for specific location based environmental conditions. Model parameterization can improve crop productivity according to He *et al*. (2010). A lower number of experimental studies has been conducted for location/region based calibration and validation of models. To understand crop plant processes of growth, development and yield, calibration of model is prerequisite for development of suitable management and adaptation strategies for cotton that will ultimately lead to sustainable crop productivity with efficient utilization of resources (Jones *et al*., 2003; Boote *et al*., 2010). A well calibrated DSSAT model with correct genetic coefficients for each cultivar can be more helpful for site specific planning of crop management with better resource utilization, and a good tool for quantification of climate modification and their impacts on crop that can support in development of improved ideotype which will be more climate resilient (Anothai *et al*., 2008). Models also support in development of ideotypes with higher crop productivity that perform under specific agro-climatic conditions. Furthermore, model can be helpful to indicate interaction between environment, crop management and genotype (Meinke *et al*., 2001; Yin *et al*., 2004). CROPGRO-Cotton model was also used for quantification of cotton yield gap by analysis of yield variability based on spatial and temporal variation (Jones *et al*., 2003). Variability in seed cotton yield under various environmental conditions in response to different performance of same cultivars was predicted by crop simulation models with relevant set of genetic coefficients (Hoogenboom, 2000; Bannayan *et al*., 2004; Makowski *et al*., 2006). Several types of crop models, e. g. mechanistic and regression models, are widely used globally by scientists for estimation of crop biomass, phenological stages, and overall yield at accurate level of prediction depicting suitability of crop models (Raes *et al*., 2009). Impact of weather elements on phenology, growth and seed cotton yield of cotton in various regions were simulated with the help of model. Climate change impact on cotton yield was evaluated by Pathak *et al*. (2007) with some climate projections of Cameroon region after adjustment of a range of cotton parameters in CROPGRO-Cotton. Calibration and validation was done and model performed well under specific climatic conditions. Further evaluation of model revealed that model respond differently to various management practices (Thorp *et al*., 2014b; Modala, 2014). Models can be promising tools for resource management. Efficient utilization of resources with better management practices can be achieved with models and cotton production risks with respect to limited available resources of water, land, nutrients and climatic extreme events and their variability can be highlighted with crop models (Boote *et al*., 2010). Field experiments can perform best with several decisions indicated by crop models through a well demonstrated mechanism and proved a well-established decision support tools for crop management under all conditions (Evett and Tolk, 2009). These models proved to be proficient research tools for development of long term and short-term crop management strategies with well-organized usage of time and available input resources for crop (Farage *et al*., 2007; Malone *et al*., 2007).

According to Iqbal (2011), DSSAT performed well under agro-ecological conditions of Punjab for simulation of seed cotton yield. Simulation results revealed that model over predicted cotton yield within an acceptable range 9-15 percent difference whereas 9-15 and 10-17 percent difference for LAI and TDM, respectively. DSSAT model was run by Shabbir (2007) for determination of leaf, stem and boll biomass. Model performance was good after model calibration and results depicted that lower RMSEs of 165, 195, 509 kg ha^{-1} were computed for leaf, stem and boll biomass, respectively. Another experimental result showed that model simulated final yield of crop with high accuracy having RMSE of 312 kg ha^{-1}, which supports reliability of model. Meanwhile, validation results with next year were also well (Guerra *et al*., 2005; Messina *et al*., 2005). Day (2001) proposed that simulation modeling and decision support system support research understandings and model for different crop ongoing processes and model prediction result increase demand of best crop production strategies for some management action for agricultural community. Climate change impact on crop predicted by models can reduce possible pressure on farming system. Clear understanding of model processes for assessment of possible yield can help in identifying different behavior of cultivars that ultimately with the use of crop models offer yield simulating production system. Ko *et al*. (2005) developed a modified Grami model for cotton in semi-arid regions. The newly developed model was not only easy to use in agriculture but also require simple inputs and ensures its expended applicability under semi-arid regions of country for irrigated cotton productions. Especially it also have applicability to monitor regional cotton growth and lint yield mapping projects.

Crop development processes and clear understanding of differences in cultivars can provide better consideration of crop models for simulation of crop production as a function of all management practices (Kiniry *et al*., 2001). Various weather factors interrelate with final crop yield and model provide probability of any event happening due to change in internal system of crop. Weight of matured boll and boll dropping followed by buds and leaves shedding due to any abiotic stress induced by nitrogen, carbon or water are well identified by model in the form of predicting final crop yield based on a set of heuristic directions (Hanan and Hearn, 2003).

An improved model was introduced by Ko *et al*. (2005) for cotton sown under semi-arid areas. This modified and improved model was easy to handle and comprised of simplest input dataset. That model has capability to perform well under other semi-arid areas and was expanded to other regions as well for evaluation of irrigated cotton growth and yield. Model performed well for monitoring purpose and mapping regional crop growth and yield. Jenkins *et al*. (2006) conducted series of experiments to evaluate stress on upland cotton caused by nitrogen fertilizer reduced lint yield and affected fiber quality and its development in mature boll. Nitrogen stress (excess) severely disturbed crop growth, staple length, strength and other quality parameters.

Read *et al*. (2006) concluded that nutrient stress (N fertilizer) in upland cotton depresses lint yield and may disrupt fiber development. It was observed that deficiency of nitrogen directly influence cotton growth and development and nitrogen stress lowers fiber length and strength. Arshad (2006) simulated seed cotton yield under Faisalabad conditions with a model (DSSAT) for better estimation of growth, development and yield of cotton and concluded that final seed cotton yield, TDM and LAI were calibrated well with model. The model results were very closer to observed data.

2.6 Productivity of Cotton under Changed Climate Scenarios

Climate change is expected to affect agriculture in different areas of the world (Parry *et al.,* 1999). The resulting effects among various continents depend on current environmental and soil conditions, availability of resources and infrastructure use to cope with change. These differences are also expected to greatly influence the responsiveness to climate change. Change in climate may disturb processes in agroecological systems that principally cause decline in crop productivity. Changing climate in future is a collective impact of rise in day and night temperature and variability exist in rainfall patterns (Parry, 2000). Estimation and prediction of future change in climate of our ecosystems are problematic due to complex interactions between different variables.

Although it is difficult to understand complex system of different variables of climate, scientists are working on better prediction of future hazards of climatic change. These changes in the environment may result in reduction of crop productivity. It has been documented that direct or indirect shift in climate was a function variation in temperature, elevation in CO_2, change in rainfall pattern and other weather elements. These shifts can be more stressful to field crops due to temperature in comparison with changes in rainfall patterns (Gbetibouo and Hassan, 2005). Crops have somehow potential to face and adopt to these climate change but still need some new adaptive technology and development of strategies with low input use in extensive agricultural systems that are more vulnerable to change in climate (Fuhrer, 2003). One of the option to cope with climate change is to utilize crop growth models that can quantify cotton productivity.

Crop cycle and different growth stages along with crop growth and yield are drastically affected by climate and it is considered as crucial factor to crop productivity across the region. Climatic extremes especially rise in temperature harms growth and yield of cotton at any phenological stage of crop (Bradow and Davidonis, 2000). Cotton can get benefits with elevation in CO_2 level being a C_3 plant. Both, temperature and CO_2, have an interactive effect on cotton that enhanced growth, development and lint yield of cotton. Experimental results depicted that 51% cotton yield was reduced in comparison to control (4700 kg ha^{-1}) when 4°C rise in temperature ranging from 28 to 32°C and have a coefficient of determination value of 0.97 and comparatively cotton yield was decreased as simulated with the help of Crop Sys model in Punjab province of India (Jones *et al*., 2003; Jalota *et al*., 2009). Rehman *et al*. (2004) concluded that rise in summer temperature greater than 45°C in Sindh and Punjab provinces caused decrease in yield of cotton significantly. This experimental result showed that temperature play a vital role in crop growth and development and it was a critical parameter for crop production. Boll production is drastically depressed by rise in day temperature greater than 30°C for duration of almost 13 hours (Reddy *et al*., 1996). Iqbal *et al*. (2003) reported delay in boll maturation and maturation period exceeds than normal days. Late maturation also directly or indirectly affects cotton fiber quality (Subhan *et al*., 2001; Shah *et al*., 2011). Cotton genotypes that mature earlier than optimum or late in season facilitates window for other crops to grow at optimum recommended time and in this case, wheat can be grown earlier in areas where cotton-wheat cropping system is under practice (Ali *et al*., 2003).

Major impacts on crop growth and production are expected to come among others from increase in CO_2 concentration, changes in temperature, precipitation. Global warming in Asia will affect not only scheduling of the crop season but also duration of the growing period of the crop in all crop producing areas. Both General Circulation Models and Crop Simulation Models become more sophisticated in response to climate change variables and predictions will become more accurate. The use of simulation models to predict the likely effects of climate change on crop production is, of necessity, an evolving science.

Timothy (2001) studied impact of climate change on cotton production with the help of two models at the U.S. Goddard Space Flight Centre within a NASA funded project. He concluded that cotton yield is neither affected by climate change on large nor on small scale. He further added that if CO_2 levels continued to rise at their present rate there would be 26-36% increase in cotton yields as predicted by the models in their study. Wang *et al.* (2008) studied impact of climate change on phenology and yield of winter wheat and spring cotton in north west China during 1981-2004 and concluded that there was clear trend of climate warming which enhanced earliness of spring cotton as the dates of seedling emergence, budding, anthesis and boll opening became earlier by 10.9, 9.0, 13.9 and 16.9 days during 1983-2004, respectively.

Bange (2007) studied the impact of climate change on cotton productivity in Australia and concluded that increase in CO_2 concentration 406-445 ppm in 2020 and 473-555 ppm in 2050 would increase photosynthetic rate of cotton by 23 to 29%. WUE would also be improved leading to increased yields. Temperature increase in the beginning and end of season would have positive effects while increase in number of severe and hot days during anthesis and boll filling would have negative impacts. In a report of National Conference of State Legislatives-2008 in Tennessee USA it was concluded that cotton is projected to thrive under high levels of temperature and CO_2. The yield increases are estimated to 6-37% and capital of 1.2 million $.

2.7 Geographic Information System

A geographic information system (GIS) allows us to question, visualize, analyze and understand the data to disclose patterns, relationships and trends. One of the most important aspects of different GIS tools are that its users can utilize any GIS resource such as maps, imagery and geodatabases (Gao *et al*., 2003).

Henry and Yoshida (2008) developed soil fertility and crop yield maps in the province of Bukidnon, Minjdanao Philippines. GIS analysis showed that the 45% of the total area of three provinces was suitable for farming purpose. Map overlay approach was used to develop the crop suitability map. Matching crops biological requirements for growth to the crop suitability maps identified the specific crops applicable in certain part of the province. The recommended crops were rice, sugarcane, corn, coconut and cassava. They found through GIS analysis that there were areas in the province that has still high potential and suitability for farming purpose.

Forkuo and Abrefa (2011) reported that in recent years geo-computational methods were used for recording, storing, processing and retrieval of data from many soil observation and elevation. The aim was to create digital maps of soil and creating a database of interactive geographic crop yield. Geographic database for analysis sustainability of the crop land was created with Microsoft SQL Server and ESRI ArcGIS. Attributes data was taken such as soil pH, effective soil depth, drainage, slope gradient, course texture and base saturation. The climatic conditions such as temperature, precipitation and length of the dry season were recorded. These attributes had been associated with spatial data to build a model database of geographical reasons. It has been recognized as an important criterion to determine the suitability of the land. Crop Mapper was developed, which had the ability to create a soil map of the region. It can perform spatial queries using the Query Builder attributes and can perform an analysis of the suitability of soil for three soil series and three selected crops. They came to conclusion that it was a fast, friendly and gave us more accurate results.

Bernard and Yakubu (2010) reported that crop growth and yield was the outcome of various factors including climatic factors, soil type and management practices. Their paper discussed the use of GIS/GPS to predict the crop yield. The study was conducted in the Western Region of Ghana. Crop yield maps were prepared using GPS and GIS to depict the influencing factors and yield variability. Interpolation technique, Inverse Distance Weighing was used to prepare spatial distribution maps for yield and influencing factors. It was concluded that the crop yield has positive relationship with influencing factors.

Geographic information can be a good indicator for investigation of within field spatial and temporal variability of cotton. Classification is crucial step in interpretation of these variations of crop yield and GIS has potential for estimation of yield on large scale and decision making in site-specific management systems (Boydell and McBratney, 2002).

CHAPTER–3

MATERIALS AND METHODS

3.1 SITE AND SOIL

The proposed study was conducted at three locations of Punjab (Figure 3.1) viz, Department of Agronomy Research Area at University of Agriculture, Faisalabad (31.26 ºN, 73.04 ºE), Cotton Research Station (CRS) at Sahiwal (30.40 ºN, 73.06 ºE) and Central Cotton Research Institute (CCRI.) at Multan (30.12 ºN, 71.26 ºE) during the summer season of 2014 and 2015.It aimed at assessing the impact of climate change on Bt cotton cultivars using crop models and GIS tools. Soil samples collected were analyzed before crop sowing. Information regarding experimental sites i.e. longitude, latitude, altitude and soil parameters i.e. physical, chemical and morphological properties were also noted for crop model and GIS mapping. Climate of each experimental site was given in Table 3.1. Figure 3.1 represents the GIS map of experimental sites.

Table 3.1: Climatic Conditions of Three Experimental Sites

Location	Latitude ºN	Longitude ºE	Altitude (m a.s.l*)	Representative Climate (Köppen-Geiger classification)
Faisalabad	31.26	73.04	184	Dry semi-arid
Sahiwal	30.40	73.06	172	Wet semi-arid
Multan	30.12	71.26	123	Dry Arid

*a.s.l: above sea level

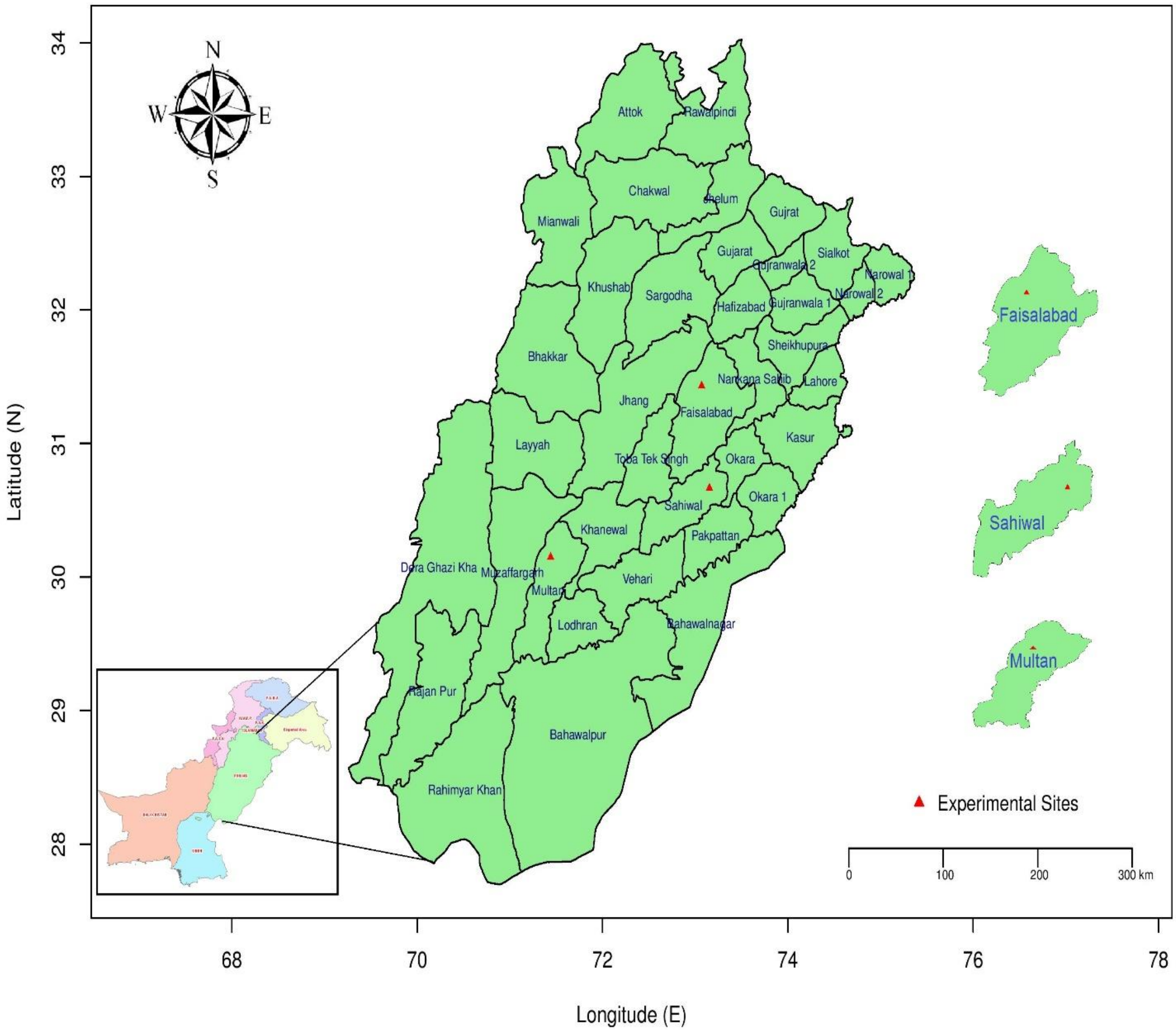

Figure 3.1: Map of experimental sites (Faisalabad, Sahiwal, Multan) developed with R.

Path (1.5m)																				**Main Water Channel**
N.E.A (Non-Experimental Area)																				
	S_1									**S_2**										
	V_1			V_2			V_3			V_1			V_2			V_3				
N.E.A	N_2	N_1	N_3	N_3	N_2	N_1	N_3	N_1	N_2	N_2	N_1	N_3	N_3	N_2	N_1	N_3	N_1	N_2	**N.E.A**	
N.E.A																				
Sub-water Channel (1m)																				
N.E.A																				
	S_2									**S_1**										
	V_2			V_3			V_1			V_2			V_3			V_1				
N.E.A	N_1	N_2	N_3	N_1	N_3	N_2	N_1	N_3	N_2	N_1	N_2	N_3	N_1	N_3	N_2	N_1	N_3	N_2	**N.E.A**	
N.E.A																				
Path (1.5m)																				
N.E.A																				
	S_1									**S_2**										
	V_3			V_1			V_2			V_3			V_1			V_2				
N.E.A	N_2	N_1	N_3	N_1	N_2	N_3	N_3	N_2	N_1	N_2	N_1	N_3	N_1	N_2	N_3	N_3	N_2	N_1	**N.E.A**	
N.E.A																				
Sub-water Channel (1m)																				

Figure 3.2: Layout of the two-year experiment conducted at Faisalabad, Sahiwal and Multan, Pakistan

3.1.1 Soil Analysis

(A) Mechanical analysis

Soil samples at 30 cm depth were collected randomly from different portions of experimental field. Furthermore, a composite sample of soil was obtained before sowing during both years with the help of soil auger. To record different physico-chemical parameters, composite soil sample from Faisalabad and Sahiwal was analyzed at soil fertility section, Ayub Agricultural Research Institute, Faisalabad in laboratory of Agricultural Chemist and soil sample from Multan experimental field was analyzed at Central Cotton Research Institute, Multan.

Bouyoucous hydrometer method is best known to determine sand, silt and clay percentage. For this, 1% sodium hexametaphosphate $(NaPO_3)_6$ was used as a dispersing agent. Sand, silt and clay percentage was determined. Soil samples were further analyzed to determine textural classes with the help of international textural triangle described by Moodie *et al*. (1959). Table 3.2 shows soil type of the three experimental sites.

(B) Chemical analysis

Chemical analysis of soil samples was done with the methodology developed by Homer and Pratt (1961) to record soil pH, organic matter, phosphorus and potassium. Again, composite soil samples were collected after crop harvest for analysis from each site. Chemical analysis of soil samples from Faisalabad showed that soil series was known as Lyallpur soil series. A well-drained soil of fine silty loam, brown in color and calcareous in its nature was observed. Low organic matter (0.35%) was recorded due to oxidation of organic matter enhanced by warm temperature. Soil pH (H_2O) is a degree of the alkalinity and acidity in soils. Soil pH at Faisalabad was 8 as soil pH increased with increase in the depth. Phosphorous value was 3.2 ppm whereas potassium level was 180 ppm. At Sahiwal, soil series was known as Jaranwala soil series. soil was well drained fine silty loam, also brown in color and calcareous in nature having very low organic matter (0.42%) but bit higher than organic matter at Faisalabad. Soil pH recorded with soil chemical analysis was 8.4. Phosphorous level was 14.8 ppm. Potassium level observed at Sahiwal was 200 ppm. At Multan, soil series was known as Miami soil series. Soil at that site was well drained fine course loam, brown in color having low organic matter (0.63%). Soil pH was 8.63. Phosphorous was 8.64 ppm while potassium was 143 ppm. Soil chemical analysis data was described in Table 3.2.

3.2 DESIGN AND TREATMENTS

The experiment was planned in split-split plot design replicated thrice (Figure 3.2). Sowing dates were kept in main plots, cotton cultivars were placed in sub plots, whereas various nitrogen levels were kept in sub-sub plots. Experiment was comprised of following treatments.

A	**=**	**Sowing Dates (main plots)**
SD_1	=	1^{st} May
SD_2	=	1^{st} June
B	**=**	**Cultivars (sub plot)**
V_1	=	FH-114
V_2	=	FH-142
V_3	=	MNH-886
C	**=**	**Nitrogen levels (sub-sub plot)**
N_1	=	150 (kg ha^{-1})
N_2	=	200 (kg ha^{-1}), (standard / Recommended)
N_3	=	250 (kg ha^{-1})

Table 3.2: Soil attributes of three locations

Location	Latitude	Longitude	Altitude	Soil Textural Class	Soil pH (H_2O)	O.M	P (available)	K
	ºN	ºE	(m)	USDA Classification	-	%	(ppm)	(ppm)
Faisalabad	31º 26	73º 04	184	Lyallpur (loam) (Fine loamy, silty, therm)	8.0	0.35	3.2	180
Sahiwal	30º 40	73º 06	172	Jaranwala (loam) (coarse-silty, mixed, hyperthermic type Calciargids)	8.4	0.42	14.8	200
Multan	30º 12	71º 26	123	Miani (loam) (Fine, silty loam, mixed, hyperthermic)	8.63	0.63	8.64	143

Soil pH and other soil attributes are the average values of 15-30 cm soil depth

3.3. Crop husbandry

Crop management practices during both crop growing seasons were kept similar and summarized in Table 3.3 and 3.5. Cotton was sown on 1st May and 1st June keeping net plot size of each experimental unit 3 m × 6 m. Crop was sown with bed-furrow method at all three locations having 75 cm apart rows and seed rate 25 kg ha^{-1} was used for the experiment. Seed was first delinted with acid before sowing that completely removes all lint over it for many benefits. Planting density was maintained by keep a uniform distance between cotton plants of 30 cm with thinning process just after crop emergence. Other agronomic management practices that include irrigation, weeding, plant protection measures, thinning etc. were done normally and uniformly for all the treatments in experiment. High quality and well approved pesticide and insecticide were sprayed on plants to control insect pest infestation ad to them below economic threshold level (ETL) by implementing some good agricultural practices (GAP). Weeds were controlled using integrated weed management practices. Under chemical control, a pre-emergence herbicide Pendimethalin (33%) at rate of 2.5 L for one hectare was sprayed. Manual weed control methods such as intercultural, hand weeding and mechanical operations were adopted. During both crop growing seasons, six times crop was sprayed with pesticide/herbicide under plant protection measures at Faisalabad, Sahiwal and Multan except 1st May sown crop at Sahiwal and 1st June sown crop at Multan where five sprays of pesticide/herbicide were done. Fertilizer was applied as recommended by Punjab Agriculture Department. Phosphorus was applied in the form of TSP [$Ca(H_2PO_4)_2$] at the rate of 115 kg ha^{-1}, whereas potassium was added to soil at the rate of 95 kg ha^{-1} in the form of SOP [(K_2SO_4)] at start of sowing. Nitrogen was incorporated into soil 1/3rd of the treatment at start of the sowing. Remaining 2/3rd of nitrogen fertilizer was added in two splits, first split where nitrogen was applied with first irrigation and second split at the flowering stage in the form of urea. Sowing plan for both years are shown in Figure 3.2.

Table 3.3: Data Collection - 2014

Locations / Operation	Faisalabad		Sahiwal		Multan	
	1st May	1st June	1st May	1st June	1st May	1st June
Sowing dates	01-05-14	01-06-14	01-05-14	01-06-14	01-05-14	01-06-14
Emergence date	05-05-14	04-06-14	05-05-14	04-06-14	06-05-14	03-06-14
Germination count	09-05-14	07-06-14	09-05-14	07-06-14	09-05-14	07-06-14
Cultivation	27-04-14	30-05-14	26-05-14	30-05-14	26-05-14	30-05-14
Cultivation	01-05-14	01-06-14	01-05-14	01-06-14	01-05-14	01-06-14
Plant protection measures						
1st spray	14-06-14	06-07-14	20-06-14	03-07-14	09-06-14	07-07-14
2nd spray	06-07-14	14-08-14	08-07-14	09-08-14	07-07-14	10-08-14
3rd spray	14-08-14	30-08-14	15-08-14	03-09-14	12-08-14	31-08-14
4th spray	30-08-14	16-09-14	30-08-14	10-09-14	25-08-14	14-09-14
5th spray	16-09-14	06-10-14	13-09-14	07-10-14	14-09-14	27-10-14
Final spray	06-10-14	27-10-14	-	27-10-14	13-10-14	-
Fertilizer						
N@150kg ha^{-1}	01-5-14	01-6-14	01-5-14	01-6-14	01-5-14	01-6-14
N@200kg ha^{-1}	13-6-14	08-7-14	12-6-14	07-7-14	12-6-14	07-7-14
N@250kg ha^{-1}	01-7-14	01-08-14	02-7-14	03-08-14	02-7-14	02-08-14

Table 3.4: Growth data sampling dates - 2014

Locations / Samples	Faisalabad		Sahiwal		Multan	
	SD_1	SD_2	SD_1	SD_2	SD_1	SD_2
1	01-6-14	01-7-14	01-6-14	01-7-14	01-6-14	01-7-14
2	20-6-14	20-7-14	20-6-14	20-7-14	20-6-14	20-7-14
3	10-7-14	10-8-14	10-7-14	10-8-14	10-7-14	10-8-14
4	31-7-14	31-8-14	31-7-14	31-8-14	31-7-14	31-8-14
5	20-8-14	20-9-14	20-8-14	20-09-14	20-8-14	20-9-14
6	10-9-14	10-10-14	10-9-14	10-10-14	10-9-14	10-10-14
7	30-9-14	30-10-14	30-9-14	30-10-14	30-9-14	30-10-14

Table 3.5: Data Collection 2015

Locations / Operation	Faisalabad		Sahiwal		Multan	
	1st May	1st June	1st May	1st June	1st May	1st June
Sowing dates	01-05-15	01-06-15	01-05-15	01-06-15	01-05-15	01-06-15
Emergence date	05-05-15	04-06-15	05-05-15	04-06-15	06-05-15	03-06-15
Germination count	09-05-15	07-06-15	09-05-15	07-06-15	09-05-15	07-06-15
Cultivation	27-04-15	30-05-15	26-05-15	30-05-15	26-05-15	30-05-15
Cultivation	01-05-15	01-06-15	01-05-15	01-06-15	01-05-15	01-06-15
Plant protection measures						
1st spray	14-06-15	06-07-15	20-06-15	03-07-15	09-06-15	07-07-15
2nd spray	06-07-15	14-08-15	08-07-15	09-08-15	07-07-15	10-08-15
3rd spray	14-08-15	30-08-15	15-08-15	03-09-15	12-08-15	31-08-15
4th spray	30-08-15	16-09-15	30-08-15	10-09-15	25-08-15	14-09-15
5th spray	16-09-15	06-10-15	13-09-15	07-10-15	14-09-15	27-10-15
Final spray	06-10-15	27-10-15	-	27-10-15	13-10-15	-
Fertilizer						
N@150kg ha^{-1}	01-5-15	01-6-15	01-5-15	01-6-15	01-5-15	01-6-15
N@200kg ha^{-1}	13-6-15	08-7-15	12-6-15	07-7-15	12-6-15	07-7-15
N@250kg ha^{-1}	01-7-15	01-08-15	02-7-15	03-08-15	02-7-15	02-08-15

Table 3.6: Growth data sampling dates - 2015

Locations / Samples	Faisalabad		Sahiwal		Multan	
	SD_1	SD_2	SD_1	SD_2	SD_1	SD_2
1	01-6-15	01-7-15	01-6-15	01-7-15	01-6-15	01-7-15
2	20-6-15	20-7-15	20-6-15	20-7-15	20-6-15	20-7-15
3	10-7-15	10-8-15	10-7-15	10-8-15	10-7-15	10-8-15
4	31-7-15	31-8-15	31-7-15	31-8-15	31-7-15	31-8-15
5	20-8-15	20-9-15	20-8-15	20-09-15	20-8-15	20-9-15
6	10-9-15	10-10-15	10-9-15	10-10-15	10-9-15	10-10-15
7	30-9-15	30-10-15	30-9-15	30-10-15	30-9-15	30-10-15

3.4. GIS Base-Mapping

Data points were taken using MAGIS (ODK), Google Earth V.10 and Online Platform "Geosurvey.com". Base maps of crop were developed using Geographic Information System software (ArcGIS V 10) and statistical software (RStudio version 1.0.153).

3.5. OBSERVATIONS

Crop growth, development and yield data were collected using standard method. Half area in each experimental plot was used for crop growth and developmental data and remaining half was utilized for recording yield and yield components data of crop.

3.5.1. CROP DEVELPOMENT

Various changes in crop life cycle was recorded by selecting five plants randomly in each plot. Those plants were tagged to measure calendar days of various phenological events, such as emergence, anthesis, boll formation and final crop maturity. Mean of number of calendar timings to different phenological stages was recorded.

A) Growing Degree Days

Growing degree days (thermal time) was calculated according to formula described by Gallagher *et al*. (1983) where daily maximum temperature and daily minimum temperature were used along-with a specific base temperature of cotton. Thermal time (Tt) is described as a function of mean temperature above a base or threshold temperature (Tb/Tt).

$$Tt = SUM\ \left[\frac{(Tmax + Tmin)}{2} - Tb\right]$$

Where Tmax is the maximum temperature, Tmin is the minimum temperature, T_b is the base temperature considered as 15°C for cotton (FAO, 2003).

B) Crop phenological parameters

1. Days taken to emergence
2. Days taken to flower initiation
3. Days taken to boll initiation
4. Days taken to maturity

1. Days taken to emergence

Number of days taken to emergence was observed by visiting experimental field on daily basis and first five plants emerged in each plot were noted and then mean numbers of days taken by seeds to emergence counted.

2. Days taken to flowering

Number of days taken to flowering stage was observed by selecting and tagging five plants randomly to observe their date of 50% flowering. Experimental field was visited regularly for this observation. The average number of days taken to flowering stage was noted from date of crop sowing.

3. Days taken to boll formation

Number of days taken to boll formation was recorded from same tagged plants in each experimental unit. Boll formation date was noted and then average days to boll formation were worked out from date of sowing.

4. Days taken to maturity

Total number of days taken by plant to complete life cycle was noted from same tagged plants in each plot. Furthermore, mean days to maturity were worked out from date of sowing.

3.5.2 CROP GROWTH

A) Sampling

Crop growth data was measured by selecting three plants randomly and then harvested from each experimental unit at twenty days interval after crop sowing during the crop season (Table 3.4 and 3.6). First harvest was thirty days after sowing whereas rest of six harvest for growth data were twenty days after sowing. Fresh weight of each fraction of plant (stem and leaf, squares, flowers and opened/un-opened boll when present) was recorded on a high accuracy electronic balance. Furthermore, these collected samples were sun dried for 48 hours duration and then dried in an oven at 65°C to get a constant weight of samples. Dry weight of sample was recorded. Total dry matter (TDM) of plant was calculated at each harvest from these measurements. A sub sample of 10 g of leaf was used to measure leaf area with the help of leaf area meter (Licor, model 3100, LI COR inc. Lincoln, NE). Leaf area of whole plant was calculated from sample leaf area. From the measurements of leaf area and oven dry weights following growth indices were calculated.

B) Calculation of Growth Indices

i) Leaf area index

Leaf area index (LAI) characterizes plant canopies. It was calculated as the ratio of upper one-sided leaf surface area to ground surface area according to Watson (1952).

$$LAI = \frac{Leaf\ Area}{Land\ Area}$$

ii) Leaf area duration (days)

Leaf area duration (LAD) represents the persistence of leave to stay green to intercept solar radiation and to convert it into dry matter and it was estimated as suggested by Hunt (1978). All LAD values were added to calculate cumulative LAD at final harvest.

$$LAD = (LAI_1 + LAI_2) \times \frac{(T_2 - T_1)}{2}$$

where LAI_1 and LAI_2 are leaf area indices at times T_1 and T_2, respectively.

iii) Crop growth rate (g m^{-2} d^{-1})

Crop growth rate (CGR) was be calculated as proposed by Hunt (1978) at each sampling date. All calculated CGRs at each destructive harvest were added to get average value of CGR.

$$CGR = \frac{(W_2 - W_1)}{(T_2 - T_1)}$$

where W_1 and W_2 are biomass increase at times T_1 and T_2, respectively.

iv) Net assimilation rate (g m^{-2} d^{-1})

Net assimilation rate (NAR) was estimated by using the formula proposed by Hunt (1978).

$$NAR = \frac{TDM}{LAD}$$

where TDM and LAD are the total dry matter and leaf area duration, respectively, at final harvest.

3.5.3. RADIATION UTILIZTION EFFICIENCIES

Radiation utilization efficiencies (RUEs) for total dry matter (TDM) and seed-cotton yield (SCY) was computed as the ratio of total biomass accumulated and seed cotton yield to cumulative PAR (∑Sa). By multiplying fraction of intercepted radiation (Fi) with daily incident PAR (Si), amount of intercepted PAR (Sa) was determined. Photosynthetically active radiation (PAR) was assumed to be equal to 50% (half) of total incident radiation on earth (Szcicz, 1974) whereas Fi was measured from Beer's law as proposed by Monteith and Elston (1983).

$$Fi = 1 - exp^{(-K \times LAI)}$$

$$Sa = Fi \times Si$$

$$RUE_{TDM} = \frac{TDM}{\sum Sa}$$

$$RUE_{YIELD} = \frac{Seed\ Cotton\ Yield}{\sum Sa}$$

where K is an extinction coefficient for total radiation. Its constant value for cotton is equal to -0.77 according to Rosenthal and Gerick (1990). On the other hand, value of RUE was estimated from the regression of TDM on accumulated PAR as suggested by Monteith (1981).

3.5.4. YIELD AND YIELD COMPONENTS

Yield and yield components were recorded from remaining half plot area where ten plants were selected and tagged randomly from each treatment plot for the determination of different yield components. All plants were picked manually for estimation of overall plot yield and converted into kg ha^{-1}. Data on following parameters was collected from tagged plants using standard procedures:

i. Number of plants m^{-2} at harvest

Total number of plants present in each plot was counted at maturity and it was divided with plot area to get number of plants m^{-2}.

ii. Plant height (cm)

Plant height was determined at crop harvest by selecting ten plants randomly from each plot with the help of a meter rod. Plant height was measured starting from soil surface to the tip of the plant and then mean value was calculated.

iii. Number of monopodial branches per plant

Number of monopodial/vegetative branches per plant was counted from ten randomly selected plants in each plot and then average number of monopodial branches were calculated.

iv. Number of sympodial branches per plant

Number of sympodial/fruiting branches per plant was also counted from ten randomly selected plants in each plot and average number of sympodial branches were calculated.

v. Number of boll per plant

Total number of bolls formed per plant was counted by selecting ten plants randomly and numbers of bolls were recorded daily. Average number of bolls formed per plant was calculated.

vi. Number of un-opened bolls per plant

For unopened bolls present per plant, same ten randomly selected plants were observed at final crop maturity and % of unopened bolls per plant was calculated as under:

$$Unopened\ bolls\% = \left[\left(\frac{Unopened\ bolls\ per\ plant}{Total\ bolls\ formed\ per\ plant}\right) \times 100\right]$$

vii. Number of opened bolls per plant

Already selected ten plants were picked separately and number of opened bolls per plant were counted, and then the average was calculated.

viii. Average boll weight (g)

Ten randomly selected plants were manually picked from each plot to calculate boll weight. Average weight of boll was computed by dividing total yield of seed cotton per plant by the total number of bolls picked from that specific plant. Average of the boll weight per plant was calculated for each plot.

i**x. 100-Cotton seed weight (g)**

100-Cotton seeds (delinted) were selected randomly from each plot and their weight was taken to get 100-Cotton seed weight.

x. Seed cotton yield (kg ha^{-1})

Crop was picked only once at its harvest stage. Seed cotton weight per plot was weighed. Furthermore, seed cotton yield was measured on per hectare basis (kg ha^{-1}).

xi. Ginning outturn (GOT) %

Seed cotton samples collected from field were sun dried for few hours before ginning. Dust and inert matter in the samples were removed. Cleaned samples were further weighed and ginned separately using single roller electric ginner in Department of Plant Breeding and Genetics of university. Lint obtained from each sample during ginning process was weighed and GOT % was computed by using following formula.

$$GOT\ (\%) = \left[\left(\frac{Weight\ of\ the\ lint}{Weight\ of\ seed\ cotton}\right) \times 100\right]$$

xii. Harvest index (%)

The harvest index (HI) is defined as economic yield of crop over biological yield. Harvest index was measured using following formula:

$$HI\ (\%) = \left[\left(\frac{Seed\ Cotton\ Yield}{Biological\ Yield}\right) \times 100\right]$$

3.5.5. QUALITY PARAMETERS

Data was recorded for yield and fiber quality at final crop maturity. Various fiber quality parameters (fiber length, strength, fiber fineness) were recorded using standard protocols with high Volume Instruments (HVI-900SA), a fiber testing system manufactured by M/S. Zellweger user Ltd. At Department of Fiber Technology at university.

Standard test methods described by ASTM (1997) were utilized for measurement of fiber quality. The yarn was spun with the help of a miniature spinning machine. Yarn was assessed for lea-strength and count strength product. Moreover, yarn lea-strength was determined with the help of yarn strength tester, whereas yarn count was determined by using skein method. A lea of 120 yards was fed to the instrument for determination of yarn strength. Count strength product value was found by multiplying the count value with the respective lea-strength of the spun yarn. The procedure of testing was adopted as mentioned in ASTM standards (ASTM, 1997).

Following quality parameter were recorded:

1. Fiber fineness (micronaire)
2. Fiber length (mm)
3. Fiber strength (g/tex)

3.6. STATISTICAL ANALYSIS

All the data obtained was statistically analyzed by employing split-split plot design using statistical package (Statisticx 8.2) on a computer. Differences among treatment means was compared for both year by the honest significant difference (HSD) test at 0.05 probability level as suggested by Steel *et al*. (1997). The year analysis was done as described by (Gomes and Gomes, 1984).

3.7. WEATHER DATA

The data for weather parameters was obtained for each site from the nearest weather observatory. Each observatory records daily maximum and minimum air temperature (°C), rainfall (mm), and daily sunshine hours. DSSAT system's tool weatherman has option for conversion of sunshine hours to daily solar radiation (M J m^{-2} day^{-1}). Historical observed data on these parameters from 1984 to 2015 was also obtained from Pakistan Meteorological Department and used as input data for CROPGRO-Cotton Model in DSSAT V 4.6.

3.8. CROP GROWTH MODELING

3.8.1 Model description

Field data obtained from the experiment during 2014 and 2015 growing season was used for calibration and evaluation of DSSAT Model. CROP GROW-Cotton Model was developed by the scientists of IBSNAT (International Benchmark Sites Network) project was run within DSSAT (Hoogenboom *et al*., 1994) environment. This model has capabilities to simulate daily crop growth, development and yield under different set of climatic and soil conditions with different agronomic managements and thus it was selected for the study. Decision Support System calculated crop genetic coefficients for Agro-Technology Transfer (DSSAT) programme, using sub module sensitivity analysis selecting the best treatment simultaneously at all three locations and unselecting other treatments. The model was run using experimental data of year 2014 for calibration and for genetic co-efficient calculation but the validity of the model was assessed by using the independent set of data recorded during year 2015 with same set of crop genetic coefficient. The weather series for changed climatic conditions were obtained by modification of observed weather series (Wolf and Van Diepen, 1995).

3.8.2 Input dataset for CROPGRO-Cotton Model

Data collected from experiment were used as input data for calibration and evaluation of the crop model. Standard meteorological data, soil data, plant characteristic and crop management data were obtained for each site and were used as input data for the model.

Weather observations (maximum temperature, minimum temperature, precipitation solar radiation) were acquired from three locations to make weather file (W file), Site information (latitude, longitude, altitude, soil physical, chemical and morphological properties) from all locations were used to make soil file (S build), crop management data regarding tillage, plant population, planting geometry, seed rate, sowing depth, irrigation application, fertilizers, detail of chemicals applied were used to create Crop management file (X file). A set of genetic coefficients that describes cultivars in terms of development and seed cotton /lint biomass and means of treatments in model language (A & T files) are also required to run the model. The model simulation was performed under optimum growth conditions. The comparison of model simulations with the observations assessed accuracy of the model (Hoogenboom *et al*., 2004). Crop phenological stages of cotton were recorded by randomly tagging five plants in each plot to record calendar time (Photo thermal days) between different phenological phenophases up to cotton picking and harvest. Photo thermal time (days) up to flowering, boll, seed, boll maturity (EMFL, FLSH, FLSD and SDPM respectively) were used as input dataset in model calibration. Information related to seed filling duration (photo thermal days) for boll and time required for a cultivar to reach final boll load under optimal conditions (photo thermal days) were also used in the cultivar file as input data used for model calibration. Days to flowering (ADAT) and boll maturity (MDAT) were included in average (A) file and these parameters were tested in calibration and model evaluation. Three randomly selected plants from one-meter length were harvested at ground level with 20 days interval after establishment of crop from each plot and appropriate boarders were left during the both growing seasons to evaluate the plant growth and its portioning to different plant components. Fresh weight of each fraction (leaf, stem, flowers, squares and boll opened and unopened) were recorded using a sensitive electronic balance. These samples were dried under sun for 48 hours and then dry weight was determined at 65°C in an oven to a constant weight. From these measurements, total dry matter (TDM) was calculated at each harvest and it was used as CWAM and CWAD kg ha^{-1} in A and T file of CSM-CROPGRO-Cotton model respectively. Similarly, an appropriate sub-sample of green leaf lamina was also used to record leaf area by leaf area meter. Leaf area index (LAI) was then calculated as the ratio of leaf area to land area (Watson, 1947).

Maximum and time series LAI (LAIX and LAID) were used as input data in the model files for comparison with the simulation during model calibration and evaluation. Seed cotton yield at final harvest (SCY) was recorded for each plot and used as HWAH in A file of CSM-CROPGRO-Cotton model to make comparison with simulated data.

3.8.3 Model Parameterization

Parameterization includes categorizing parameters in CROPGRO-Cotton model that would best predict cotton growth, development and productivity according to local climatic conditions of experimental sites. The model has specific parameter information related to crop species and cultivar files which define day length sensitivity, heat unit accretion required for each specific growth and development stage. It was parameterized for simulation of each treatment studied during all growing seasons in field experiments. Crop management's inputs for model were quantified during field experiments including field initial conditions, cotton planting details, fertilizer applications, irrigation schedules, tillage information and harvest dates. Soil was analyzed up to 30 cm depth for its physical, chemical and hydrological properties before planting of cotton. Initial soil moisture content and irrigation scheduling were assessed with the aid of a neutron moisture probe for each planting date and growing season. There were no parameters available for the studied cultivars in these experiments through some Bt generic cultivars genetic parameters were existed (Wajid *et al*., 2014) but those were significantly different in growth pattern, developmental stages and cotton productivity. Specific information of cultivar parameters including phenology, growth, yield and its components were documented for each experiment unit during growing years. It was used as input data set for model calibration to get best simulation fit as compared to experimental observed data measured in the field trails.

3.8.4 Model Calibration

Calibration is a process of adjusting some model parameters to our own conditions. It is also necessary for getting genetic co-efficient for new cultivars used in modeling study. So the model was calibrated with data (that included phenology, biomass, LAI, and yield components) collected during 2014 at all locations against treatment, May sowing, cv FH-142 and 200 kg N ha^{-1} that performed best in field trials. Cultivar co-efficient successively starting from CSDL (critical short-day length) and PPSEN slope of the relative response to development to photoperiod with time to PODOUR, the time required for cultivar to reach final pod load under optimal conditions (Photo thermal days). Almost 15 Coefficients control the phenology, growth and seed cotton yield (Hoogenboom *et al*., 1994). To select the most suitable set of coefficients an iterative approach proposed by Hunt *et al*. (1993) was used. Calculated coefficients for three cotton cultivars and their detailed descriptions are given in Table 4.22.

3.8.5 Model Validation

To check the accuracy of the model simulations, it was run with data recorded against remaining treatments for all locations in the year 2014 during model calibration. The data of year 2015 was used for validation. During all this process, available observed data on crop phenology (anthesis date, maturity date), crop growth (leaf area index and total dry matter production) and seed cotton yield was compared with simulated values to get simulated values very much closer to the observed values.

3.8.6 Evaluation of Model performance using statistical indices

The procedure precision of cotton genetic coefficient estimation and performance of models were evaluated by using statistical formula equation such as: the root mean square error (RMSE), coefficient of determination (R^2), index of agreement (d) and mean predicted deviation (MPD). These statistical indices were used to determine the differences between observed and simulated parameters.

The index of agreement expresses how much the overall deviation between observed and simulated values. The added value of this statistical indicator (d) as compared to RMSE is in its ability to capture how well the model performs over the while simulation span. The d is unit-less and may assume values ranging from 0 to +1, with better model simulation efficiency when the values are closer to +1 (Willmott, 1982). Index of agreement (d) can be computed by using following equation

$$\mathrm{d} = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}\left(\left|P'_i\right| + \left|O'_i\right|\right)^2}\right]$$

where n is the observation number, P_i is the predicted assessment for the *i*th quantity while O_i is the observed one for the *i*th measurement. Its value ranged from 0 to 1, closer the d index values to unity (1), better the fitness and simulation of model.

Root mean square error (RMSE) were used to decide the statistical differences between observed and simulated variables (Wallach and Goffinet, 1989), it could be computed by using the following equation to determine the predictability degree (Soler *et al*., 2007).

$$\text{RMSE} = \left[\sum_{i=1}^{n} \frac{(P_i - O_i)^2}{n}\right]^{0.5}$$

Where n donates the numbers of observations used for comparisons, P_i are the simulated variables studied while O_i are the observed values used in the above equation.

Mean predicted deviation was computed by using following equation and it indicates the difference between simulated and observed variables. It was used to detect whether the model over or under simulated parameters.

$$\text{MPD} = \left[\sum_{i=1}^{n} \left(\frac{|O_i - P_i|}{O_i}\right) 100\right] / n$$

where n donates the numbers of observations used for comparisons, P_i are the simulated variables studied while O_i are the observed values used in the above equation.

Cotton cultivar coefficient estimation procedure accuracy and model performance was also evaluated by the coefficient of determination (R^2) and it was computed by using the following equation.

$$R^2 = 1 - \left[\frac{\sum_i Oi - Pi)^2}{\sum_i (Oi - Mi)^2}\right]$$

where P_i is the simulated variables and M_i is the mean value studied while O_i are the observed values used in the above equation.

3.9 CLIMATE CHANGE IMPACT ASSESSMENT

The multi-location and temporal analysis of field trial data is needed while conducting studies to document shift in spatial boundaries of crop potential areas, changes in phenology, growth and crop productivity etc. Therefore, the study was conducted on three locations representing various climatic regions in the Punjab.

Three locations that were selected for the study are presented in Table 3.1 with their environmental and soil characteristics. Climate Models used for generation of future climate data of RCP 4.5 are described in Table 3.7. The climate change scenarios formulated by

Pakistan Meteorological Department using synthetic model guided by General Circulation Model (GCM) output were selected for climate change impact assessment (Table 3.8).

3.9.1 Seasonal analysis

The climate change impacts on crop phenology; growth and yield were assessed with use of crop growth model run with weather series representing both the present and changed climates. In order that the findings obtained by a comparison of yields for different climates have a statistical significance, multi-annual (30 years) crop model simulations were run for each scenario. Climate change impact on cotton productivity was assessed by using calibrated CSM-CROPGRO-Cotton model under DSSAT V 4.6 in seasonal analysis tool.

The descriptive statistics, such as means, standard deviations characteristics were determined and used for impact assessment. This approach is considered more decisive (in a statistical sense) as compared to the use of single values related to individual years/ locations. Crop model simulations were run with observed soil, physiological, and crop management data during 2014. Observed weather series during 2014 and historical observed past data from1984-2015 was provided to CROP-GROW-Cotton Model in weatherman tool to create separate stations. Sub menu, environmental modification of seasonal analysis tool of model has addition, subtraction, multiplication and replace options for every weather element. With the help of the sub menu the selected scenarios treatments were opted and the model was run for simulations of crop phenology, growth and seed cotton yield under changed climate scenarios. The impact of climate change was estimated by comparing model crop yields simulated with use of weather series representing the present climate and the changed climate.

Table 3.7: Climate model used to generate future climate data

Model Name	**Modeling Center**	**Spatial Resolution**
Community Climate System Model (CCSM4)	National Center for Atmospheric Research (NCAR)	1.25° × 0.94°
Canadian Earth System Model (CanESM2)	Canadian Centre for Climate Modelling and Analysis (CCCMA)	2.81° × 2.81°
Earth System Model – Geophysical Fluid Dynamics Laboratory (GFDL-ESM2M)	Geophysical Fluid Dynamics Laboratory (GFDL)	2.5° × 2.01°
Hadley Centre Global Environmental Model (HadGEM2-ES)	Met Office Hadley Centre (MOHC)	1.87° × 1.25°

Source: Burhan *et al*., 2015

Table 3.8: Climate change scenarios used for study impact of climate change on seed cotton (*Gossypium hirsutum* L.) yield in Faisalabad, Sahiwal and Multan.

Location / Century	Faisalabad			Sahiwal			Multan		
	Temp. (°C)	**Rainfall**	**CO_2 (ppm)**	**Temp. (°C)**	**Rainfall**	**CO_2 (ppm)**	**Temp. (°C)**	**Rainfall**	**CO_2 (ppm)**
Early Century (2000-2039)	1.7	+44.4%	423	1.7	+37.1%	423	1.9	+105%	423
Mid Century (2040-2069)	3.7	+55.5%	499	3.7	+48.6%	499	4.2	+118%	499
Late Century (2069-2100)	7	+77.7%	556	7	+71.4%	556	7.6	+165%	556

+: Increase in rainfall

Source: Burhan *et al*., 2015

3.9.2 Strategy analysis

After assessment of climate change impact on cotton productivity at all locations seasonal analysis tool of DSSAT was run with different management options, such as sowing date, nitrogen application and varietals comparison, to mitigate the impact of climate change and sustained the crop productivity. To determine the optimum sowing date, and variety for each location, seasonal analysis driver was run. The observed historical weather data from 1984-2015 were used for assessment of best management option to maximize net return under changed climate scenarios. Measurements made about experimental sites during year 2014 were used as initial conditions for series of model runs. Biophysical and Strategic Analysis options were used to compare the results under different options.

3.10 GEOGRAPHIC INFORMATION SYSTEM

Global Positioning System (GPS) device "GARMIN eTrex 30" was used to determine coordinates of experiment place and digital layout was developed using ArcGIS V 10. Field data obtained was utilized to visualize, analyze, and interpret data. ArcGIS digitized the crop data and combined geography and crop simulated data to visualize the results of experiment. ArcGIS utilized the data and developed digital maps, imagery and geodatabases.

Cotton productivity maps were developed to evaluate the impact of climate change on cotton. Climate data was used for interpolation of potential seed cotton yield with environmental factors. Potential seed cotton yield is the maximum crop yield that can be achieved by any cultivar at a particular environmental condition without any abiotic or biotic crop stress. It is based on genetics of that particular cultivar that regulate portioning of biomass, incoming solar radiations and concentration of CO_2 (Van Ittersum and Rabbinge, 1997).

WOFOST-Cotton (World Food Studies) is a more complex model based on leaf level CO_2 assimilation. WOFOST model was run with R script to generate maps at a high temporal and spatial resolution. Model was run with 30 years' baseline weather data of WorldClim (1984-2015) and implements as R packages (R Core Team, 2017). Two methods were utilized to run WOFOST model for geospatial maps of cotton productivity at high resolution.

(1) Weather Generator: Weather generator use high spatial and low temporal (monthly data) resolution data to generate daily weather data (Jones and Thornton, 2003) that can be used to run WOFOST model.

(2) Meta Model: Metamodel is another option to simulate daily weather data and metamodel can be helpful to generate high spatial resolution data. Original model results were adjusted to aggregated original model input (e.g. mean annual temperature) (Perlman *et al*., 2013).

3.10.1 Weather data from NASA

The Prediction of Worldwide Energy Resource (POWER) datasets under NASA's applied science program were acquired from National Aeronautics Space Association. Satellites for acquisition of data were GEOS-4 and GEOS-5 for wind speed at 10 m, solar radiation, maximum, minimum and average temperature at 2m, GPCP for daily precipitation (Zhang *et al*., 2008). Weather input data derived with 1 ^{o} latitude × 1^{o} longitude spatial resolution was used as raster for Punjab province of Pakistan starting in 1984. Each cell was considered as a weather station. Figure 3.3 represents schematic diagram of research work.

3.10.2 Spatial yield prediction and generation of GIS maps

Raster package developed by Hijmans *et al*. 2016, was used to develop simulated potential seed cotton yield maps of Punjab using data from all weather stations with prediction of each spatial method. Spatial interpolation is defined as predicting the values of a primary variable at points within the same region of sample location (Burrough & McDonnel, 1998; Verdin *et al*., 2014; Ailliot *et al*., 2015).

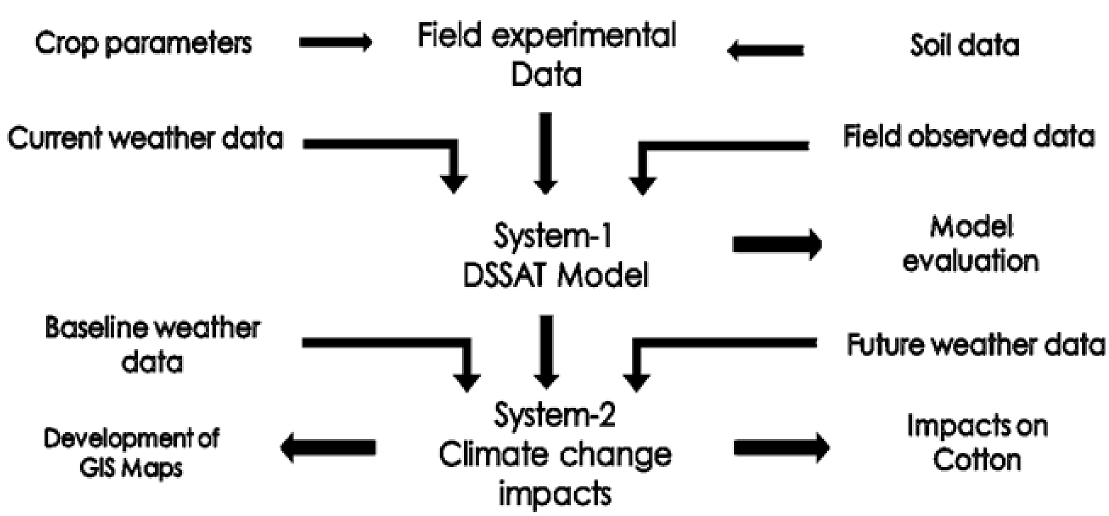

Figure 3.3: Schematic diagram of research work

CHAPTER–4

RESULTS AND DISCUSSION

4.1. WEATHER

Weather is the present combination of atmospheric elements (physical condition of the atmosphere) at a specific time and location, and the resulting processes seasonally and daily. Climate is long term weather conditions in a region. According to Köppen-Geiger classification, climate of Faisalabad features a dry semi-arid climate and climate of Sahiwal features wet semi-arid climate whereas climate of Multan features dry arid climate. Figure 4.1 illustrates daily weather data (maximum, minimum and mean temperature, Rainfall) of three locations during crop growing seasons of 2014 and 2015.

4.1.1. Weather of experimental sites during crop season

Fluctuations in weather was observed during crop growing season for both years at all three experimental areas. Rainfall pattern was very uncertain with high variability and maximum precipitation occurred during monsoon in the months of July and August that significantly affected crop yield specially in 2015 (Figure 4.1). High rainfall was experienced at Faisalabad (264.4 mm) during crop growth period than Sahiwal (143 mm) and Multan (134.1 mm) in 2014. Comparatively higher rainfall was experienced during 2nd year with 303 mm, 295.7 mm and 273.6 mm rainfall at Faisalabad, Sahiwal and Multan sites, respectively. Sahiwal and Multan sites were relatively warmer (1-2°C) than Faisalabad during both crop seasons.

The pattern of mean temperature was almost similar at all three locations and average temperature was higher (30-34°C) from May to August and then lowered to 18-29°C from September to November (Figure 4.1). Moreover, incident radiation was also higher at Sahiwal than Multan and Faisalabad sites that ultimately supported longer crop duration and finally seed cotton yield. Relative humidity ranged between 34-71% and 43-74% at all sites during crop seasons 2014 and 2015, respectively. Monthly mean of all weather variables (maximum temperature, minimum temperature, rainfall and solar radiation) during crop growing seasons of 2014 and 2015 are described in Table 4.1.

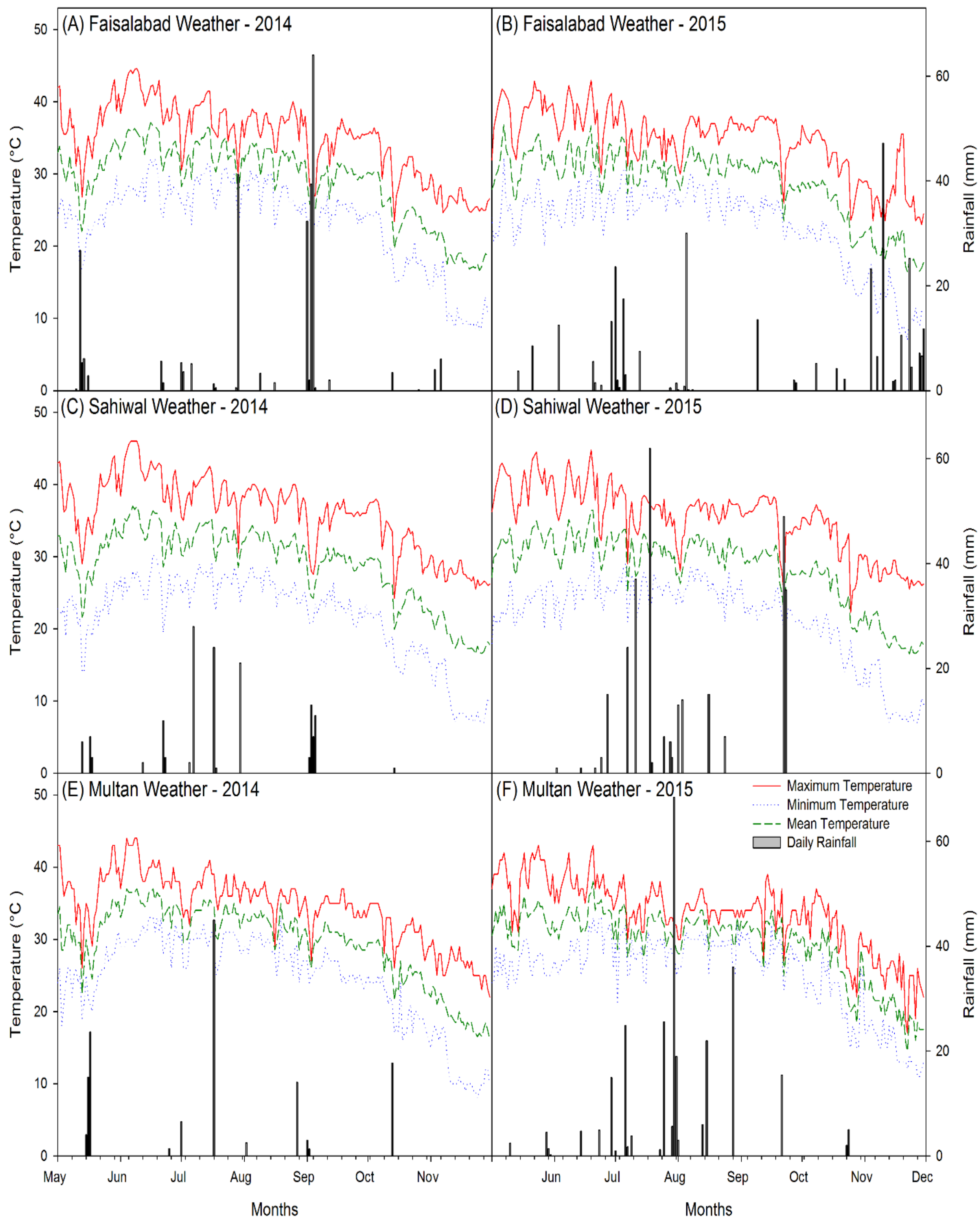

Figure 4.1: Weather conditions at Faisalabad, Sahiwal and Multan during crop growing seasons (2014 and 2015).

Table 4.1: Monthly mean of weather variables during crop growing seasons 2014 and 2015.

Month	Maximum Temp. (°C)			Minimum Temp. (°C)			Rainfall (mm)			Solar Radiation (MJ m^{-2})		
	FSD	SWL	MTN	FSD	SWL	MTN	FSD	SWL	MTN	FSD	SWL	MTN
Crop growing season – 2014												
May	36.6	37.8	36.7	23.6	22.0	24.6	41.2	16.3	42.6	24.3	26.9	23.4
June	40.9	41.8	39.9	28.0	26.2	30.4	7.1	15.2	1.4	25.1	27.6	21.4
July	37.0	38.6	36.7	27.9	26.4	29.4	57.5	76.1	51.6	20.7	24.0	18.5
August	37.1	38.2	35.7	27.3	25.9	28.4	4.8	0.2	16.5	20.0	22.5	17.1
September	33.9	34.8	34.1	24.4	22.8	25.5	140	34.1	4.3	17.1	19.1	16.1
October	31.3	32.6	31.4	19.1	17.9	20.5	3.6	1	17.7	15.7	17.2	14.8
November	26.3	27.5	26.3	11.4	9.9	11.9	10	0.1	0	13.8	14.9	13.4
Crop growing season – 2015												
May	38.6	40.2	38.7	24.8	23.3	26.4	17	0.3	8.5	25.1	27.8	23.6
June	38.0	39.0	37.6	25.5	24.9	28.9	11.6	21.2	24.5	24.6	26.2	20.5
July	34.8	36.2	34.5	27.0	25.4	28.1	128	141.1	151.2	19.7	22.7	17.1
August	35.8	35.9	33.9	26.7	25.7	29.0	48.4	49	67	19.3	20.4	14.0
September	35.3	35.1	33.8	24.3	22.6	27.9	75.2	84	15.4	18.3	19.5	13.1
October	32.1	32.5	31.2	19.0	18.0	22.0	14.5	0.1	7	16.2	17.1	13.5
November	27.1	26.7	25.1	12.0	8.9	14.9	8.8	0	0	13.7	14.3	11.3

FSD= Faisalabad **SWL=** Sahiwal **MTN=** Multan

4.1.2. Hot days and nights

Temperature is a key factor affecting rate of cotton plant developmental processes. Higher temperature with some potential extreme events directly induce crop stress and ultimately affect crop productivity (Hatfield and Prueger, 2015). Warm days and nights directly affected boll formation and ultimately crop yield. Warmer temperature during boll maturation period significantly affect (decrease) micronaire value (Bange, 2007). Hot days and nights during crop flowering stage greatly impact (shorten duration of flowering stage) on crop production.

Crop growing season in 2014 was warmer and at Faisalabad, hot days were 28 with daytime temperature greater than 40°C and hot nights were 11 with nighttime temperatures greater than 30°C as illustrated in Figure 4.3 (A). At Sahiwal, 41 hot days with maximum temperature > 40°C and one hot night with minimum temperature >30°C significantly induced heat stress as shown in Figure 4.3 (C). Hot days at Sahiwal somehow affected seed cotton yield of crop and only one hot night supported more crop yield. Similarly, Figure 4.3 (E) represents hot days and hot nights at Multan where hot days were 15 and hot nights were 29 having maximum and minimum temperature greater than 40°C and 30°C respectively. Hot night temperature at Multan drastically affected crop yield and less seed cotton yield was observed at Multan.

Crop growing season in 2015 was cooler as compared to previous year due to more rainfall at all locations. Only 19 days were recorded as warm days and 4 nights were recorded as hot nights at Faisalabad as shown in Figure 4.3 (B). Figure 4.3 (D) revealed that Sahiwal site experienced quite warmer weather as compared to other sites with 30 warm days and 1 warm night. Whereas, 15 days and 23 nights were observed as warmer at Multan as illustrated in Figure 4.3. Again, hot nights at Multan reduced seed cotton yield due to increased rate of respiration. Results are supported by Hake and Silvertooth (1990) and according to him, when higher daytime temperature persists till nighttime, it causes cotton to bum up all the stored energy to regulate normal processes of plant and also to regulate its organized structure.

Figure 4.2 represents average number of hot days (maximum temperature > 40°C) and average number of hot nights (minimum temperature > 30°C) at various locations of Pakistan. There were more than 60 days in Larkana, Bahawalpur, Jackobabad and adjacent areas where maximum temperature was great than 40°C and similarly, same areas experienced night temperature greater than 30°C for almost 60 days.

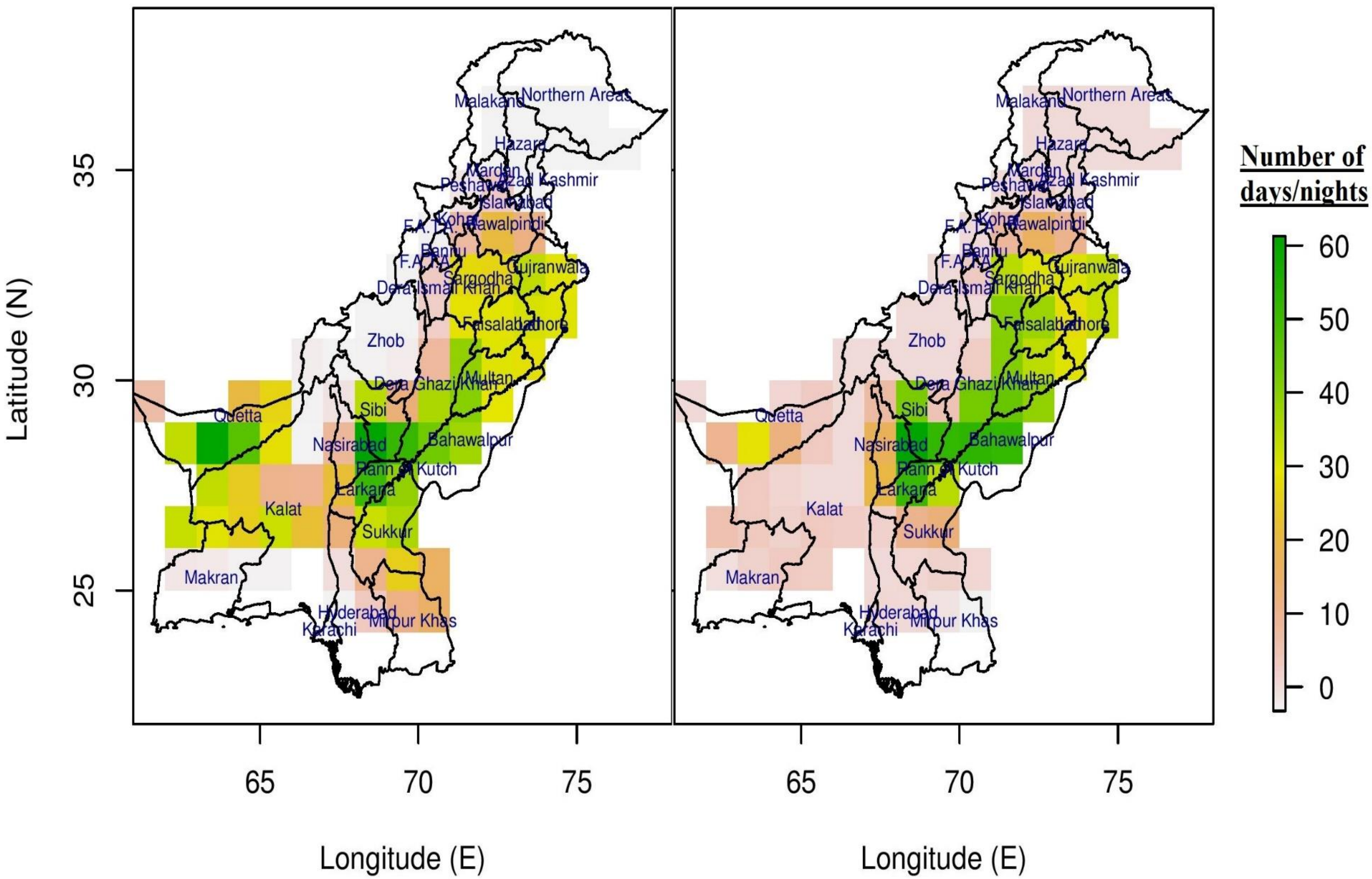

Figure 4.2: Average number of hot days and hot nights at various locations of Pakistan (left: hot days; right: hot nights)

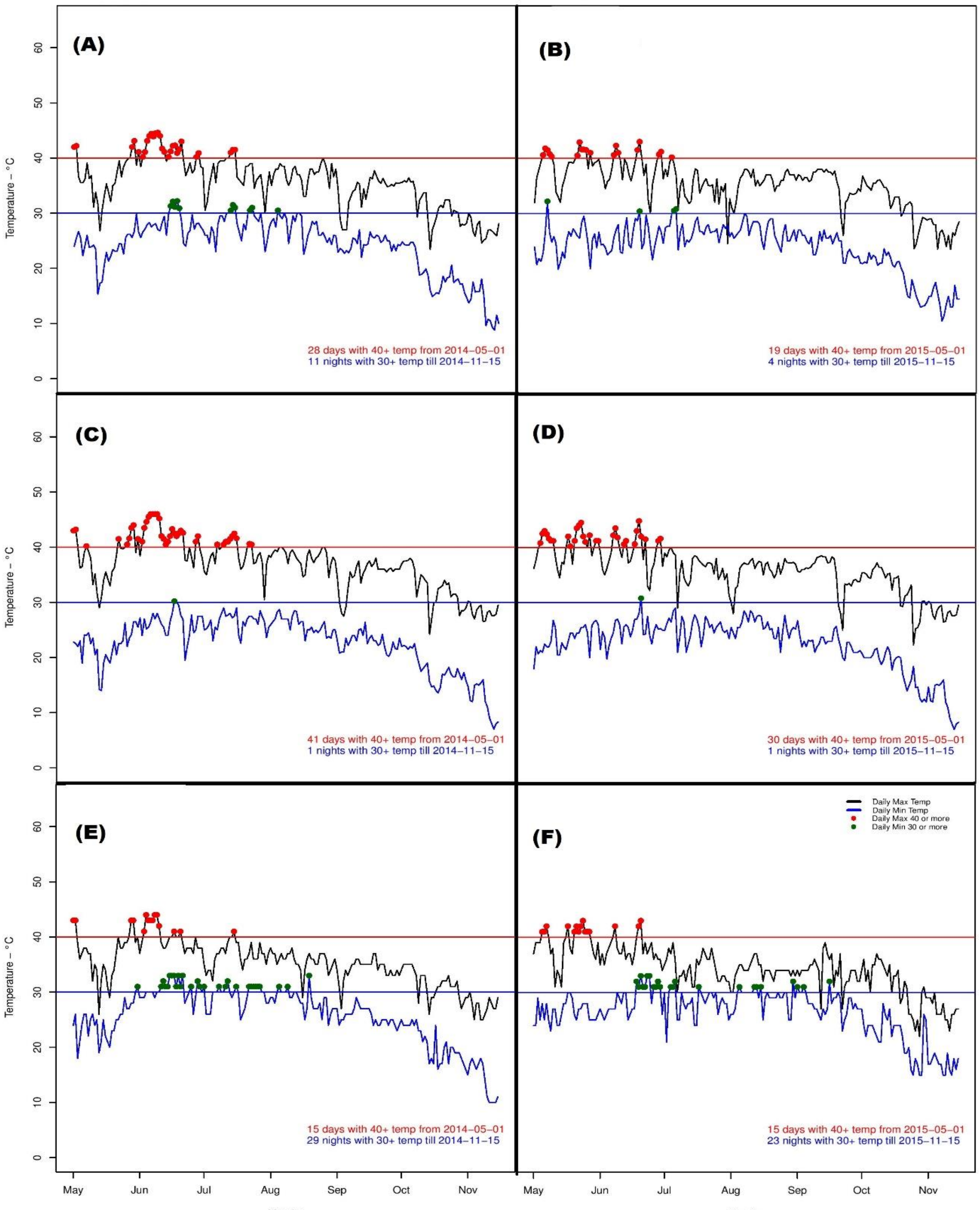

Figure 4.3: Day and night temperature at Faisalabad (A, B), Sahiwal (C, D) and Multan (E, F) during growing season of 2014 (left) and 2015 (right), respectively.

4.2. CROP DEVELOPMENT

4.2.1. Crop Phenology

Crop phenology and growth cycle are controlled by temperature, solar radiation and environmental conditions. These developmental phases of cotton were controlled mainly by temperature or photoperiod (Craufurd and Wheeler, 2009). Sowing time also regulate duration of crop phenological stages.

Crop development process in cotton plant go through a number of stages which are divided into 4 main crop growth stages for practically crop management reasons. These stages are seed germination and seedling establishment; leaf area expansion and crop canopy development; flowering and boll formation and crop maturation (Oosterhuis and Jernstedth, 1999). Transitions between successive phenological stages are subtle and not always evidently distinguishable.

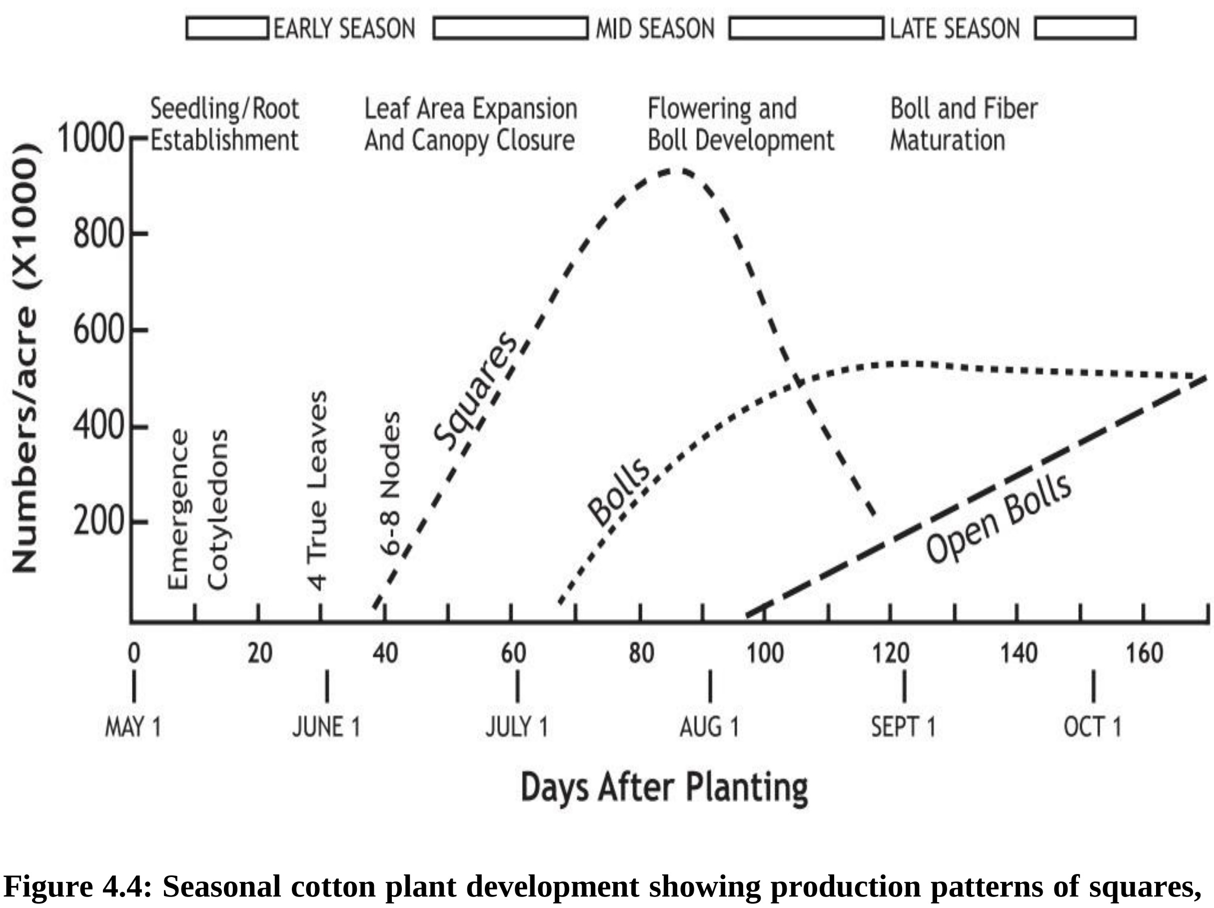

Figure 4.4: Seasonal cotton plant development showing production patterns of squares, bolls and mature bolls (Oosterhuis, 1990).

May sown crop in 2014 crop season took more days for completion of different crop stages as compared to June sown crop. Different phenological stages of cotton under study were emergence, flowering, boll formation and crop maturity (Tables 4.2 and 4.3). Emergence stages was distinguished by appearance of cotyledons above the soil surface. May sown crop took 6 days for emergence during both growing seasons at all locations while June sown crop took 5 days for appearance of cotyledons at Faisalabad and Sahiwal and 4 days at Multan. Cotton flowering started from bottom to the top of plant. Flowering, boll formation and crop maturity of May sowing was delayed by 3, 29, 8 days respectively at Faisalabad; 6, 29, 4 days at Sahiwal and 3, 28, 4 days at Multan in comparison with June sowing. As the sowing time was delayed from May onward, crop was exposed to high temperature stress resulting in early completion of phenological events especially boll development at all three locations. June sowing of cotton experienced higher temperature stress that ultimately led to short duration of phenological stages at all three locations. Similar trend was observed in 2nd year of experiment but all these crop stages were late in early and late sowing windows.

Cultivars performance was evaluated under different sowing dates at wide range of climatic conditions of Punjab. Significant differences were observed among different cultivars due to variation in growth behavior and phenotypic characteristics. FH-114 is early maturing while FH-142 and MNH-886 are medium maturing cultivars. Short duration cultivar (FH-114) completed all phenological stages in 3-6 days earlier than medium duration cultivars (FH-142 and MNH-886) during both crop seasons. More hot days and nights were recorded in 2014 than 2015 and these hot day and nights had significant impact on crop phenology. Sahiwal had more hot days and nights as compared to Faisalabad and Multan. Plant temperature above or below the thermal kinetic value result in stress that hinders crop growth and delay in completion of all phenological phases and ultimately affect the seed cotton yield and less radiation use efficiency (Luo *et al*., 2014). Late sowing significantly affected overall crop phenology especially boll development phase and crop productivity due to heat stress by shortening of crop cycle. May sown crop had increased vigor and good crop stand due to optimum climatic conditions with effective reproductive periods from square formation to boll maturing time. As temperature increased, it shortened the growth cycle and phenological phases (Sawan *et al*., 2002; Bange *et al*., 2008).

4.2.2 Thermal time of cotton phenological stages

Heat units or Growing Degree Days are simple means of relating plant growth, development, and maturity to air temperature. Heat units are often used to estimate or predict the length of different phases of development in crop plants (Ahmad *et al*., 2017). Thermal time is a controlling factor of different crop phenological stages of cotton.

Thermal time (TT) or growing degree days (GDD) is a minimum threshold temperature which is required for crop to enter into next phenological stage by acquiring specific heat units. It is relationship between temperature and crop growth stage. May sowing attained more thermal time for each phenologcial stage while June sowing took less thermal time due to high temperature stress and long photoperiod to complete life cycle (Sawan *et al*., 2002). Data presented in (Table 4.2) showed that thermal time from sowing to boll formation during 2014 was 1611.3°C days at Faisalabad, 1592.3°C days at Sahiwal and 1614°C days at Multan in May sowing. Equivalent figures in 2015 were 2236°C days, 2221°C days and 2225°C days, respectively. In June sowing, accumulation of growing degree days (GDD) were 2236°C days and 2068°C days at Faisalabad, 2221°C days and 2057°C days at Sahiwal, 2225°C days and 2092°C days and Multan during 2014 and 2015, respectively.

Heat unit’s summation is related to crop development rather than growth because crop growth is related to dry matter formation through photosynthesis. It means that crops require a particular amount of heat units to mature. If this amount is consumed by the crop, it is ready for harvesting. But it is not necessary that crop growth may also be completed. Growing degree days for complete crop duration ranged between 3053 to 3103°C days during 2014 for May sowing at all experimental sites. In 2015 the value was between 2889 and 3047°C days. For June sowing, heat units accumulated during complete growing season was between the range of 2811°C days to 2910°C days during 2014 and comparable values were 2681°C days to 2832°C days. The crop sown at Sahiwal and Multan accumulated more heat units than Faisalabad due to differences in mean temperature. Rate of heat unit accumulation and crop development increased with increase in temperature. Higher temperature shortened crop growing period with earlier crop phenological stages whereas lower temperature shortened crop growth cycle due to late or longer crop developmental stages (Hodges, 1991).

Table 4.2: Phenological data of cotton sown in May and June (2014)

Phenological Stage		Calendar Date			Calendar Days			Heat Unit (°C days)		
		FSD	SWL	MTN	FSD	SWL	MTN	FSD	SWL	MTN
Sowing	SD_1	1-May	1-May	1-May	0	0	0	0	0	0
	SD_2	1-Jun	1-Jun	1-Jun	0	0	0	0	0	0
Emergence	SD_1	7-May	7-May	7-May	6	6	6	136.5	133.7	135.5
	SD_2	6-Jun	6-Jun	5-Jun	5	5	4	135.1	135.2	115.5
Anthesis	SD_1	30-Jun	02-Jul	29-Jun	60	62	59	1237.3	1254.7	1252.5
	SD_2	28-Jul	27-Jul	27-Jul	57	56	56	1239.5	1222.9	1266.5
Boll Formation	SD_1	18-Jul	18-Jul	17-Jul	78	78	77	1611.3	1592.3	1614
	SD_2	18-Sep	18-Sep	14-Sep	109	109	105	2236.1	2220.8	2224.5
Crop Maturity	SD_1	03-Oct	4-Oct	1-Oct	155	156	153	3070.05	3052.9	3103
	SD_2	26-Oct	31-Oct	28-Oct	147	152	149	2810.8	2838	2909.5

FSD= Faisalabad **SWL=** Sahiwal **MTN=** Multan

***Base temperature** = 15°C

SD_1 =1^{st} May

SD_2 = 1^{st} June

Table 4.3: Phenological data of cotton sown in May and June (2015)

Phenological Stage		Calendar Date			Calendar Days			Heat Unit (°C days)		
		FSD	**SWL**	**MTN**	**FSD**	**SWL**	**MTN**	**FSD**	**SWL**	**MTN**
Sowing	SD_1	1-May	1-May	1-May	0	0	0	0	0	0
	SD_2	1-Jun	1-Jun	1-Jun	0	0	0	0	0	0
Emergence	SD_1	7-May	7-May	7-May	6	6	6	135.45	131	146.5
	SD_2	6-Jun	6-Jun	5-Jun	5	5	5	108.2	107.05	117.5
Anthesis	SD_1	29-Jun	28-Jun	29-Jun	59	58	59	1188.8	1213.7	1237
	SD_2	28-Jul	28-Jul	27-Jul	57	57	56	1131.3	1133.6	1166
Boll Formation	SD_1	19-Jul	17-Jul	17-Jul	79	77	77	1576.5	1556.9	1602
	SD_2	15-Sep	16-Sep	13-Sep	107	107	104	2068.8	2057	2091.5
Crop Maturity	SD_1	29-Sep	30-Sep	1-Oct	151	152	153	2914.4	2889.5	3047
	SD_2	28-Oct	29-Oct	28-Oct	149	150	149	2710.9	2679.5	2831.5

FSD= Faisalabad **SWL=** Sahiwal **MTN=** Multan

***Base temperature** = 15°C

SD_1 =1^{st} May

SD_2 = 1^{st} June

4.2.3. Plant height (cm)

Crop sown on the different sowing dates significantly differed for plant height during both growing season at all locations. Data regarding number of plant height for different sowing dates, cultivars and nitrogen levels along-with its interaction at three locations (Faisalabad, Sahiwal and Multan) for two years (2014 and 2015) are presented in Table 4.4. Highly significant differences ($P<0.01$) were observed among sowing dates, cultivars and nitrogen rates during both growing seasons at all locations. However, interactive effects between sowing dates vs cultivars, sowing dates vs nitrogen rates, cultivars vs nitrogen rates and among sowing dates, cultivars and nitrogen rates remained non-significant ($P>0.05$). Year analysis showed that first growing season (2014) with optimum weather conditions attained more plant height than second year at all locations but statistically non-significant relationship was observed.

Plant height of various cultivars sown on 1st May and 1st June at three locations were significantly different. May sown crop produced 17.3% (140.7 vs 116.3 cm) more plant height as compared to June sown crop due to longer crop duration and more radiation utilization. Crop plants at Sahiwal were (4.6% and 2.5%) taller than crops gown at Faisalabad and Multan during growing seasons of 2014 and 2015 respectively. It might be due to more sunshine hours and hot weather during both growing seasons at Sahiwal. Results are in agreement with Hussein (2005) who worked under similar conditions.

Experimental results showed that long stature cultivars (FH-142 and MNH-886) attained more plant height in comparison with short stature cultivar (FH-114) during both growing seasons at all locations. Taller plants were produced by cultivar FH-142 which were at par with cultivar MNH-886 followed by cultivar FH-114 of smaller plants at all locations due to its genetic characteristics. On an average of all locations, maximum plant height (141.50 cm) was produced by cultivar FH-142 followed by cultivar MNH-886 (131.66 cm) while shorter plant heights were observed in cultivar FH-114 (112.6 cm). Plant height is a genetic characteristic of crops parameter which is also influenced by environmental factors.

Significant response of nitrogen rates was observed on plant height at all locations. Increase in nitrogen dose also increased its vegetative growth that ultimately contributed to taller plants. Averaged over locations, maximum plant height (133.7 cm) was produced at 250 kg ha^{-1} nitrogen level which was statistically at par (128.4 cm) with 200 kg ha^{-1} nitrogen while smaller plants (123.7 cm) were recorded in experimental plots where 150 kg ha^{-1} nitrogen was applied. Results were in contrary to the findings of Hussein (2005); Wiatrak *et al*. (2005); Clawson *et al*. (2006).

Table 4.4: Plant Height (cm) as affected by site, sowing date and nitrogen rate for three cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	139.38 A	137.72 A	154.66 A	137.71 A	138.05 A	136.38 A	140.65
SD_2= 1st June	117.12 B	117.12 B	109.11 B	117.05 B	118.83 B	118.35 B	116.26
HSD 5%	8.12	7.43	44.16	1.93	8.12	7.51	-
Significance	**	**	*	**	**	**	-
(B) Cultivar							
V_1 = FH-114	113.44 B	111.78 B	118.12 B	107.98 C	112.78 B	111.6 B	112.61
V_2 = FH-142	141.98 A	140.15 A	143.60 A	141.86 A	141.31 A	140.15 A	141.50
V_3 = MNH-886	131.89 A	130.33 A	133.93 A	132.30 B	131.22 A	130.33 A	131.66
HSD 5%	11.58	11.57	14.73	6.14	11.58	11.34	-
Significance	**	**	**	**	**	**	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	124.00 B	122.33 B	127.30 B	123.12 B	123.33 B	122.17 B	123.70
N_2= 200 kg ha^{-1}	128.91 AB	127.19 AB	131.52 AB	127.13 AB	128.24 AB	127.30 AB	128.38
N_3= 250 kg ha^{-1}	134.41 A	132.74 A	136.82 A	131.89 A	133.74 A	132.63 A	133.70
HSD 5%	5.55	5.59	6.16	6.96	5.55	5.55	-
Significance	**	**	**	*	**	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	129.10	127.42	131.88	127.38	128.44	127.36	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.2.4. Number of Monopodial branches per plant

Monopodial branches are also called vegetative or non-fruiting branches which are larger than sympodial or fruiting branches (Chaudry and Guitchounts, 2003). Sowing dates had less effect on monopodial branches as mostly it relates with genetics of cultivars. Data regarding number of monopodial branches per plant for different sowing dates, cultivars and nitrogen levels along-with its interaction at three locations (Faisalabad, Sahiwal and Multan) for two years (2014 and 2015) are presented in Table 4.5. Highly significant differences ($P<0.01$) were observed among sowing dates, cultivars and nitrogen rates during both growing seasons at all locations. However, interactive effects between sowing dates vs cultivars, sowing dates vs nitrogen rates, cultivars vs nitrogen rates and among sowing dates, cultivars and nitrogen rates remained non-significant ($P>0.05$). Year analysis showed that number of monopodial branches were alike in both crop growing seasons.

Experimental data revealed that sowing dates significantly affected number of monopodial branches on a plant at all locations during both growing seasons. A higher number of monopodial branches (3.11) was observed in May sown crop in comparison with June sown crop. Late planting significantly affected number of monopodial branches and minimum number of monopodial branches (1.72) were recorded in late sowing. Other scientists (Arshad *et al*., 2007; Iqbal, 2011; Li *et al*., 2014) reported similar observations.

Cultivars are categorized into two groups, erect type and spreading type. FH-114 was erect type cultivar which had less canopy cover and fewer monopodial branches as compared to cultivars FH-142 and MNH-886 which are spreading type or bushy cultivars and have more number of monopodial branches per plant. Cultivar FH-114 produced maximum number of monopodial branches (3.22) while MNH-886 and FH-142 produced less monopodial branches (2.09 and 1.93), both being significantly at par with each other.

Nitrogen rates significantly affected number of monopodial branches per plant at locations. By increasing nitrogen dose, monopodial branches also increased significantly. Higher number of monopodial branches (2.74) were observed at 250 kg ha^{-1} nitrogen level which were at par with 200 kg N ha^{-1} during both growing seasons (Table 4.5). Minimum number of monopodial branches (2.04) were recorded at 150 kg N ha^{-1}. Similar results were reported by Aslam *et al*. (2013).

Table 4.5: Number of monopodial branches as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	3.56 A	3.22 A	2.95 A	2.86 A	3.14 A	2.93 A	3.11
SD_2= 1st June	1.45 B	2.35 B	2.13 B	1.86 B	1.11 B	1.44 B	1.72
HSD 5%	0.73	0.79	0.74	0.36	0.69	1.33	-
Significance	**	*	*	**	**	*	-
(B) Cultivar							
V_1 = FH-114	3.37 A	3.62 A	3.33 A	3.38 A	2.81 A	2.84 A	3.22
V_2 = FH-142	2.01 B	2.30 B	2.09 B	1.66 C	1.75 B	1.79 B	1.93
V_3 = MNH-886	2.14 B	2.43 B	2.19 B	2.04 B	1.81 B	1.92 B	2.09
HSD 5%	0.30	0.30	0.38	0.19	0.43	0.56	-
Significance	**	**	**	**	**	**	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	2.12 B	2.49 B	2.13 B	1.98 B	1.72 B	1.82 B	2.04
N_2= 200 kg ha^{-1}	2.59 AB	2.80 AB	2.57 AB	2.52 AB	2.12 AB	2.16 AB	2.46
N_3= 250 kg ha^{-1}	2.81 A	3.07A	2.91 A	2.58 A	2.53 A	2.57 A	2.74
HSD 5%	0.54	0.53	0.58	0.58	0.6078	0.569	-
Significance	*	*	**	*	*	*	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	2.51	2.78	2.54	2.36	2.12	2.18	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.2.5. Number of Sympodial branches per plant

Important parameter for estimation of seed cotton yield is sympodial or fruit bearing branches. Once a fruiting branch has formed at a main stem node, the cotton plant is no longer able to produce monopodial or non-fruiting branches above that node (Chaudry and Guitchounts, 2003). Data regarding number of sympodial branches per plant for different sowing dates, cultivars and nitrogen levels along-with its interaction at three locations (Faisalabad, Sahiwal and Multan) for two years (2014 and 2015) are presented in Table 4.6. Highly significant differences ($P<0.01$) were observed among sowing dates, cultivars and nitrogen rates during both growing seasons at all locations. However, interactive effects between sowing dates vs cultivars, sowing dates vs nitrogen rates, cultivars vs nitrogen rates and among sowing dates, cultivars and nitrogen rates remained non-significant ($P>0.05$).

Sowing dates significantly affected number of sympodial branches. Early sown crop produced a higher number of sympodial branches as compared to late sown crop. Experimental results depicted that higher number of fruiting branches (19.45) were produced in May sown crop during both growing season at all locations that contributed to higher seed cotton yield. These results are similar to the findings of Hussein (2005).

The development of sympodial branches are also determined by genetic characteristics and regulated by environmental conditions. Spreading or bushy type cultivars (FH-142 and MNH 886) produced higher number of sympodial branches as compared to erect type cultivar (FH-114). On an average, more fruiting branches (17.30) were produced by cultivar FH-142 followed by cultivar MNH-886 (16.04) while less number of sympodial branches (13.93) were produced by cultivar FH-114. Being an important yield component, a higher number of fruiting branches supported a higher number of bolls on a plant, which contributed to a higher crop yield and higher seed cotton yield was attained from cultivar FH-142.

Nitrogen application plays a vital role in development of higher number of sympodial branches on a plant. Higher level of nitrogen produced more sympodial branches at all locations. Nitrogen level of 250 kg N ha^{-1} produced 19% more fruiting branches than 150 kg ha^{-1} nitrogen level.

Table 4.6: Number of sympodial branches as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	19.12 A	19.79 A	22.12 A	21.12 A	18.45 A	16.12 A	19.45
SD_2= 1st June	11.97 B	12.30 B	14.97 B	12.86 B	11.30 B	8.97 B	12.06
HSD 5%	1.20	1.20	1.23	7.07	1.21	1.17	-
Significance	**	**	**	*	**	**	-
(B) Cultivar							
V_1 = FH-114	13.90 B	14.40 B	16.90 B	14.27 B	13.24 B	10.90 B	13.93
V_2 = FH-142	17.05 A	17.55 A	20.05 A	18.70 A	16.38 A	14.05 A	17.30
V_3 = MNH-886	15.68 AB	16.18 AB	18.68 AB	18.00 A	15.01 AB	12.68 AB	16.04
HSD 5%	2.67	2.67	2.67	1.71	2.66	2.67	-
Significance	*	*	*	**	*	*	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	13.81 B	14.31 B	16.81 B	14.98 B	13.14 B	10.81 B	13.98
N_2= 200 kg ha^{-1}	15.87 A	16.37 A	18.87 A	17.07 A	15.20 A	12.87 A	16.04
N_3= 250 kg ha^{-1}	16.96 A	17.46 A	19.96 A	18.92 A	16.29 A	13.96 A	17.26
HSD 5%	1.76	1.78	1.82	1.96	1.7647	1.7511	-
Significance	**	**	**	**	**	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	15.54	16.04	18.54	16.99	14.88	12.54	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.3. GROWTH INDICES

4.3.1. Leaf Area Index

Efficient utilization of light energy and conversion efficiencies depend upon radiation absorption by the green leaves because solar energy and capturing efficiency determine dry matter production. Data regarding maximum LAI for different sowing dates, cultivars and nitrogen levels along-with its interaction at three locations (Faisalabad, Sahiwal and Multan) for two years (2014 and 2015) are presented in Table 4.7. Highly significant differences ($P<0.01$) were observed among sowing dates, cultivars and nitrogen rates during both growing seasons at all locations. However, interactive effects between sowing dates vs cultivars, sowing dates vs nitrogen rates, cultivars vs nitrogen rates and among sowing dates, cultivars and nitrogen rates remained non-significant ($P>0.05$).

Higher leaf expansion was observed in 2014 as compared to 2015 due to higher solar radiation and heat unit accumulation. It is basically related to its growth (Peksen, 2007) and can be a good indicator of crop yield that regulate crop capability to produce and then translocate photosynthates to various plant structures according to Favarin *et al*. (2002); Fontes *et al*. (2005). Comparatively, crop sown on 1st May showed significantly higher leaf area index at all locations during both growing seasons over late sown cotton by 33.5% vs 32.3% at Faisalabad, at 33.5% vs 41.1% Sahiwal and 25.1% vs 20.1% at Multan. Late sown crop attained less leaf area to land area ratio. There was a significant difference between both sowing dates. Results are similar to the findings of other studies (Reddy *et al*., 2005; Singh *et al*., 2007).

Genotypic variations existed for maximum LAI and maximum LAI was recorded from cultivar FH-142 sown at Faisalabad and Sahiwal while cultivar MNH-886 produced maximum LAI at Multan site during both growing seasons. As FH-142 was developed at Cotton Research Institute, Faisalabad and MNH-886 was developed at Cotton Research Station, Multan so they perform well under respective climatic conditions. Minimum value of LAI was observed from cultivar FH-114 at all locations. On an average of all locations, maximum LAI was attained by cultivar FH-142 over other cultivars (FH-114 and MNH-886) by average value of 13.64% and 3.34%. Bange *et al*. (2003) and Wajid *et al*. (2010) confirmed my experimental findings.

Optimum nitrogen fertilizer is very important for vegetative growth of any crop. Various levels of nitrogen rates significantly affected leaf area index. Higher level of nitrogen increased vegetative growth of crop that ultimately leads to higher value of maximum leaf area index. Experimental data showed that higher dose of nitrogen (250 kg ha^{-1}) produced higher leaf area by 10.1% and 26.2% over 200 kg ha^{-1} and 150 kg ha^{-1}. Similar were the findings of Singh *et al*. (2007); Wajid *et al*. (2010).

Leaf Area Index increased progressively up to 130 days after sowing to attain its maximum value and then started to decline towards end of the growing season. Figures 4.5 and 4.6 illustrated seasonal leaf area index of May and June sown cotton at Faisalabad during 2014 and 2015. Unequivocal effect had been seen with higher rate over lower nitrogen rates and leaf area index by cultivar FH-142 was good over other cultivars. Similarly, leaf area expansion of May and June sown crop at Sahiwal are shown in Figure 4.7 and 4.8 for crop growing season of 2014 and 2015. Pronounced effect had been seen with 250 kg N ha^{-1} over other nitrogen rates and performance of cultivar FH-142 was remarkable in leaf area expansion over other cultivars. Similar trend of higher value of seasonal LAI was observed for May sown crop as compared to June sown crop at Multan as shown in Figure 4.9 and 4.10 during both years. Significant effect had been observed with higher rate of nitrogen over lower rates and performance of cultivar MNH-886 was good as compared to other cultivars.

Table 4.7: Maximum leaf area index as affected by site, sowing date and nitrogen rate for three cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	4.23 A	3.88 A	4.23 A	4.34 A	3.95 A	3.48 A	4.02
SD_2= 1st June	2.81 B	2.62 B	2.81 B	2.55 B	2.96 B	2.78 B	2.76
HSD 5%	0.30	0.75	0.37	0.60	0.74	0.49	-
Significance	**	*	**	**	*	*	-
(B) Cultivar							
V_1 = FH-114	3.20 B	3.00 B	3.17 C	3.10 B	3.21 B	2.92 B	3.10
V_2 = FH-142	3.78 A	3.45 A	3.81 A	3.73 A	3.55 AB	3.22 AB	3.59
V_3 = MNH-886	3.59 A	3.31 A	3.59 B	3.50 A	3.60 A	3.26 A	3.47
HSD 5%	0.33	0.19	0.17	0.29	0.39	0.33	-
Significance	**	**	**	**	*	*	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	2.93 C	2.79 C	2.95 C	2.81 C	2.91 C	2.68 C	2.84
N_2= 200 kg ha^{-1}	3.65 B	3.35 B	3.62 B	3.59 B	3.47 B	3.11 B	3.46
N_3= 250 kg ha^{-1}	3.98 A	3.62 A	4.00 A	3.93 A	3.98 A	3.60 A	3.85
HSD 5%	0.28	0.17	0.24	0.29	0.29	0.20	-
Significance	**	**	**	**	**	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	3.52	3.25	3.52	3.44	3.48	3.17	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

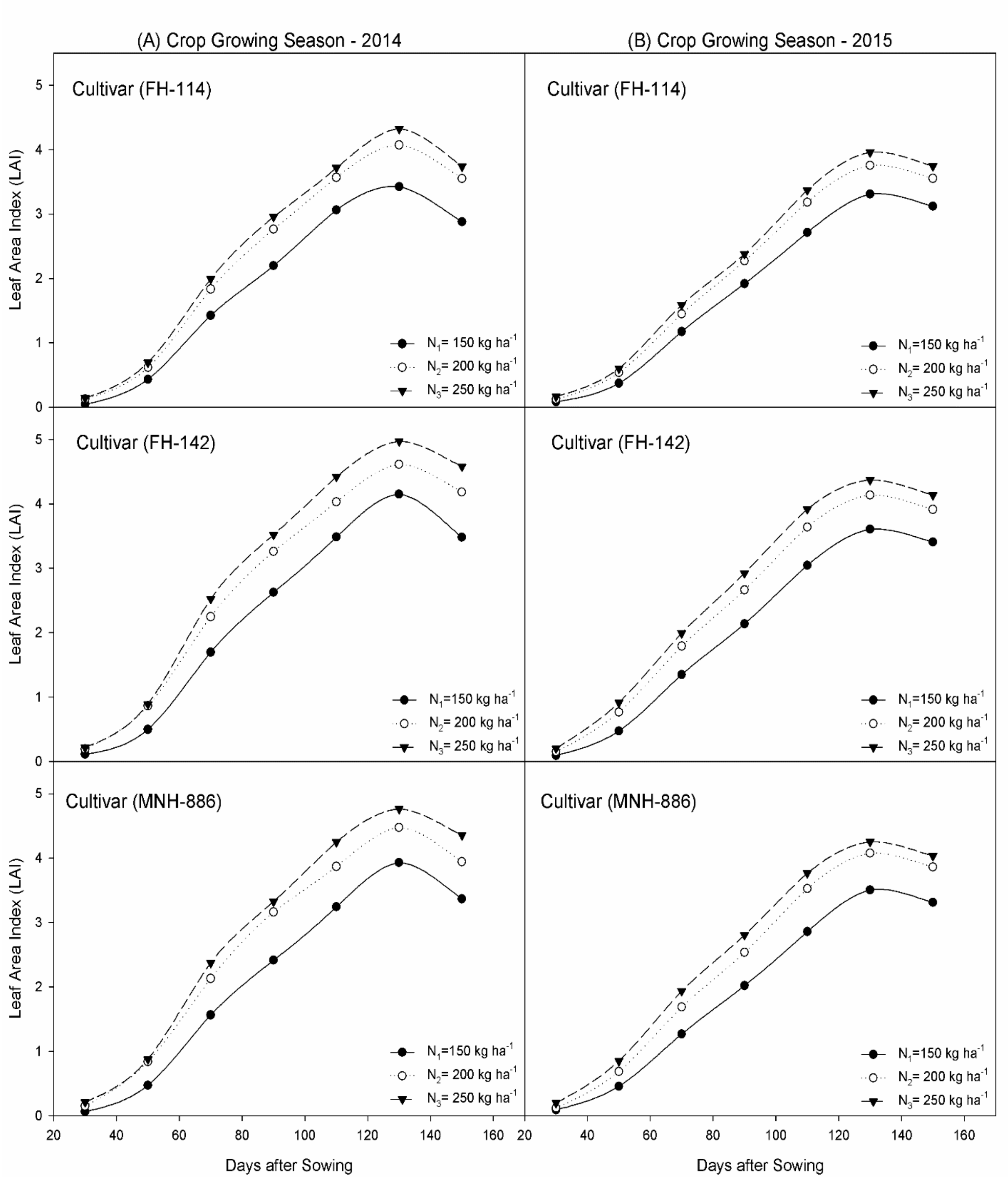

Figure 4.5: Time course change in leaf area index of different cultivars sown in the month of May at Faisalabad during crop growing seasons of 2014 and 2015.

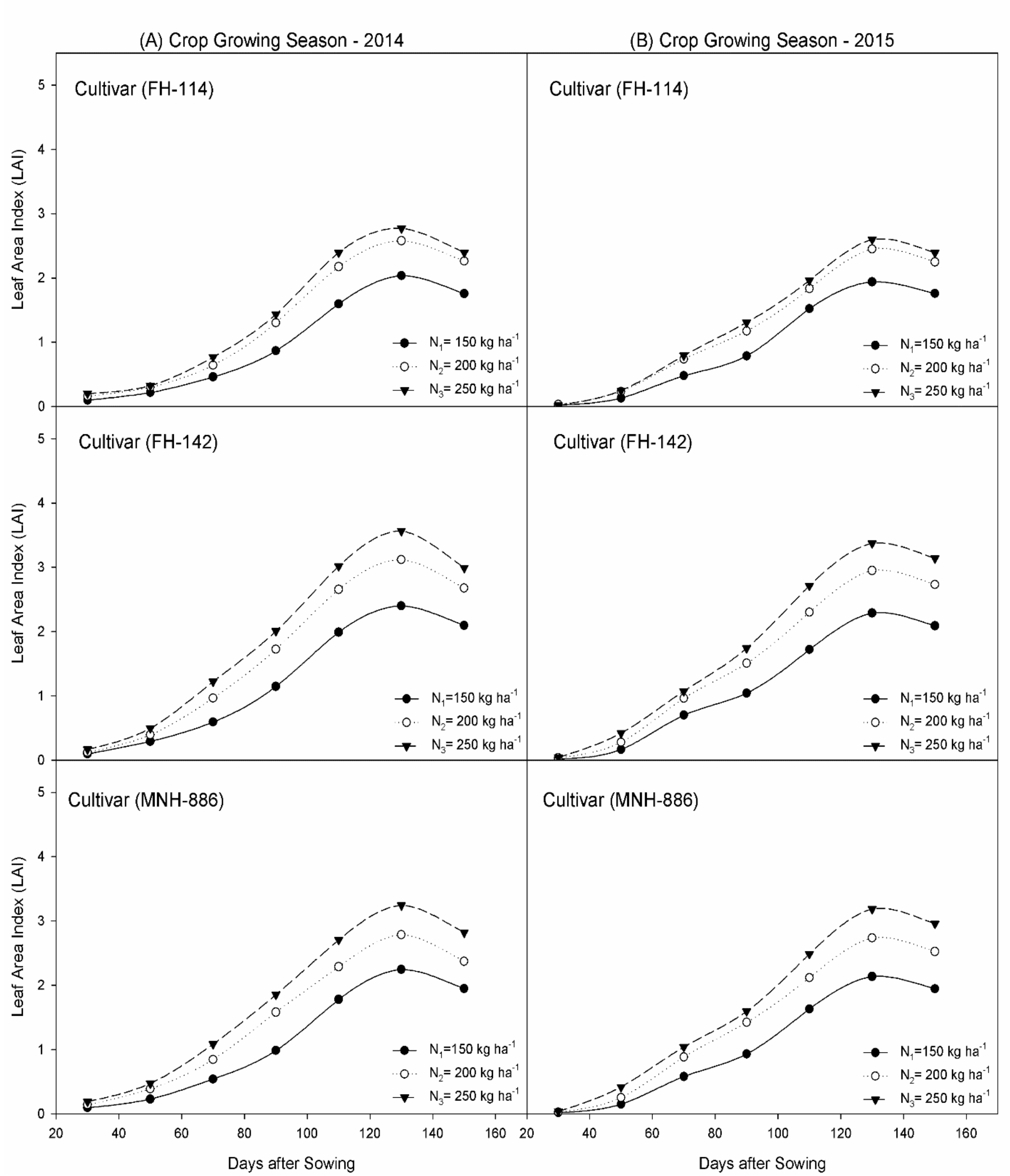

Figure 4.6: Time course change in leaf area index of different cultivars sown in the month of June at Faisalabad during crop growing seasons of 2014 and 2015.

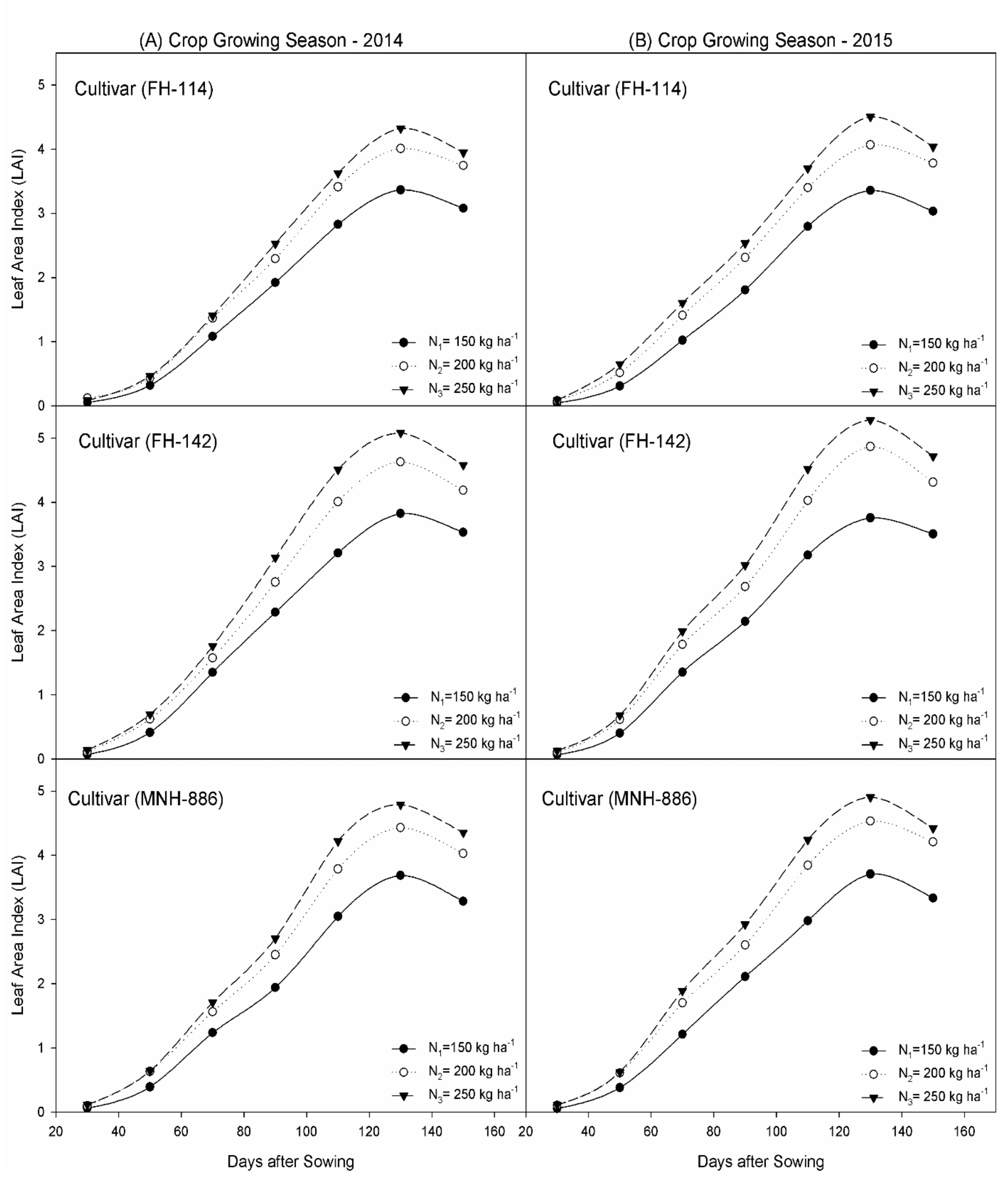

Figure 4.7: Time course change in leaf area index of different cultivars sown in the month of May at Sahiwal during crop growing seasons of 2014 and 2015.

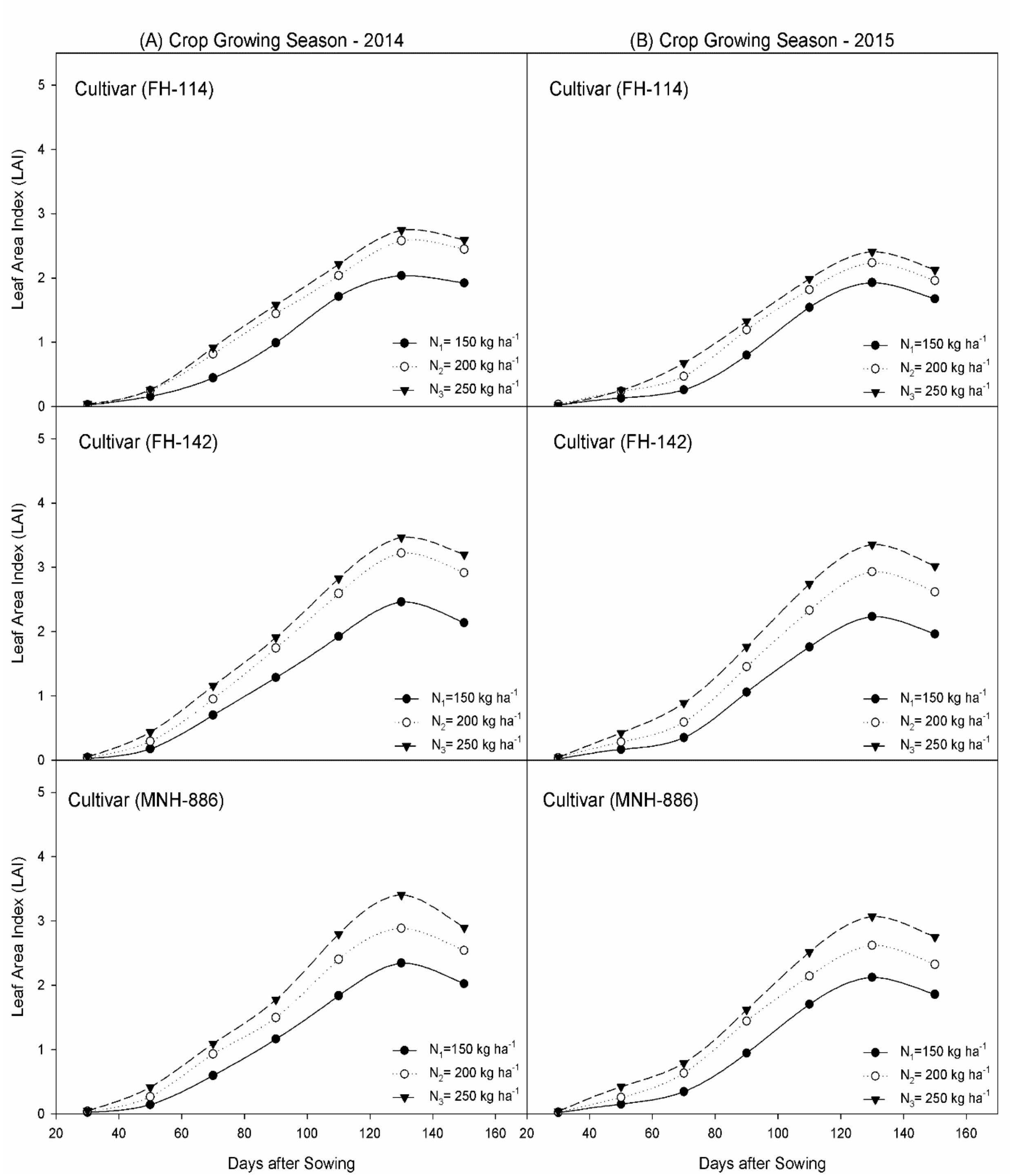

Figure 4.8: Time course change in leaf area index of different cultivars sown in the month of June at Sahiwal during crop growing seasons of 2014 and 2015.

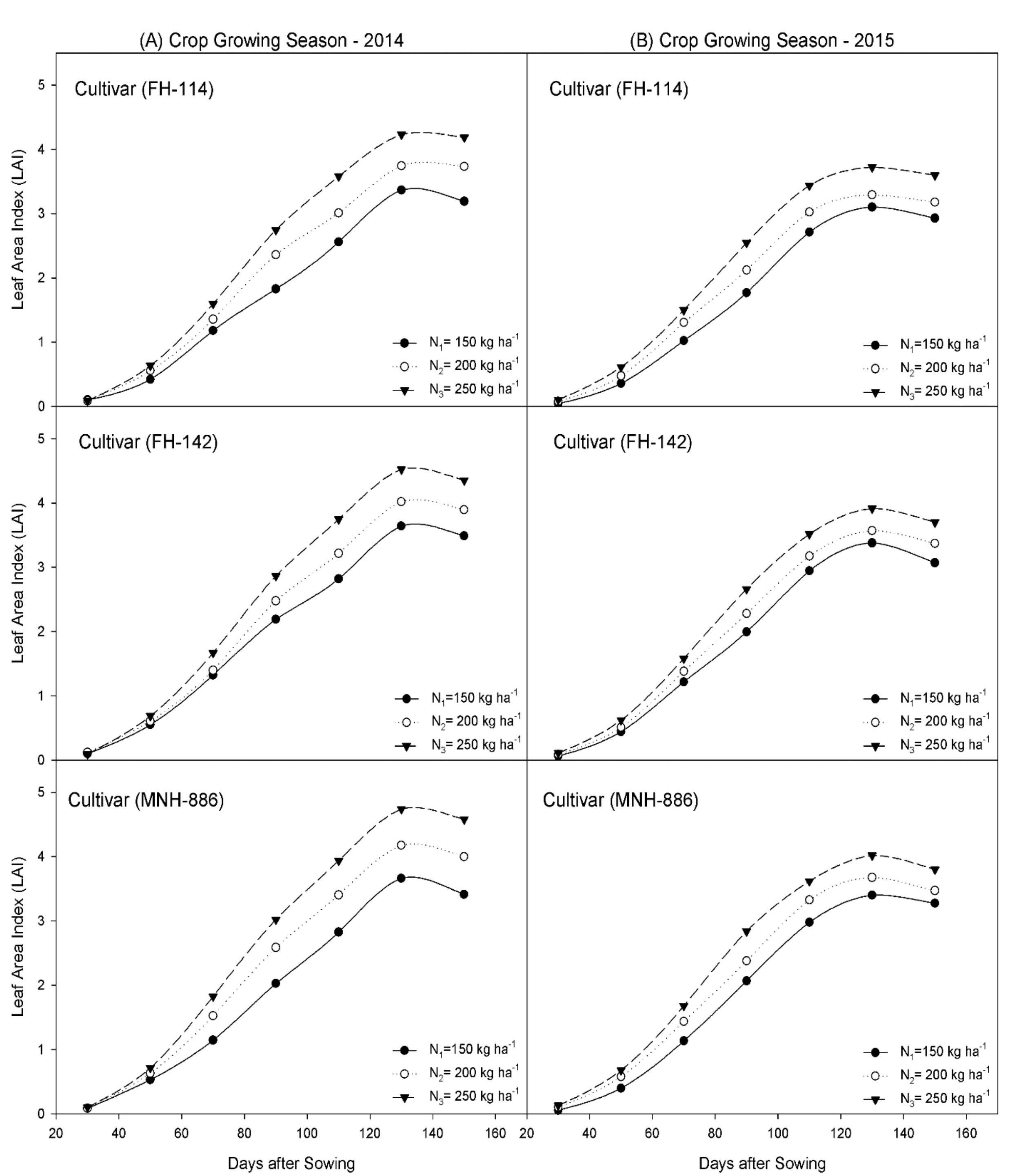

Figure 4.9: Time course change in leaf area index of different cultivars sown in the month of May at Multan during crop growing seasons of 2014 and 2015.

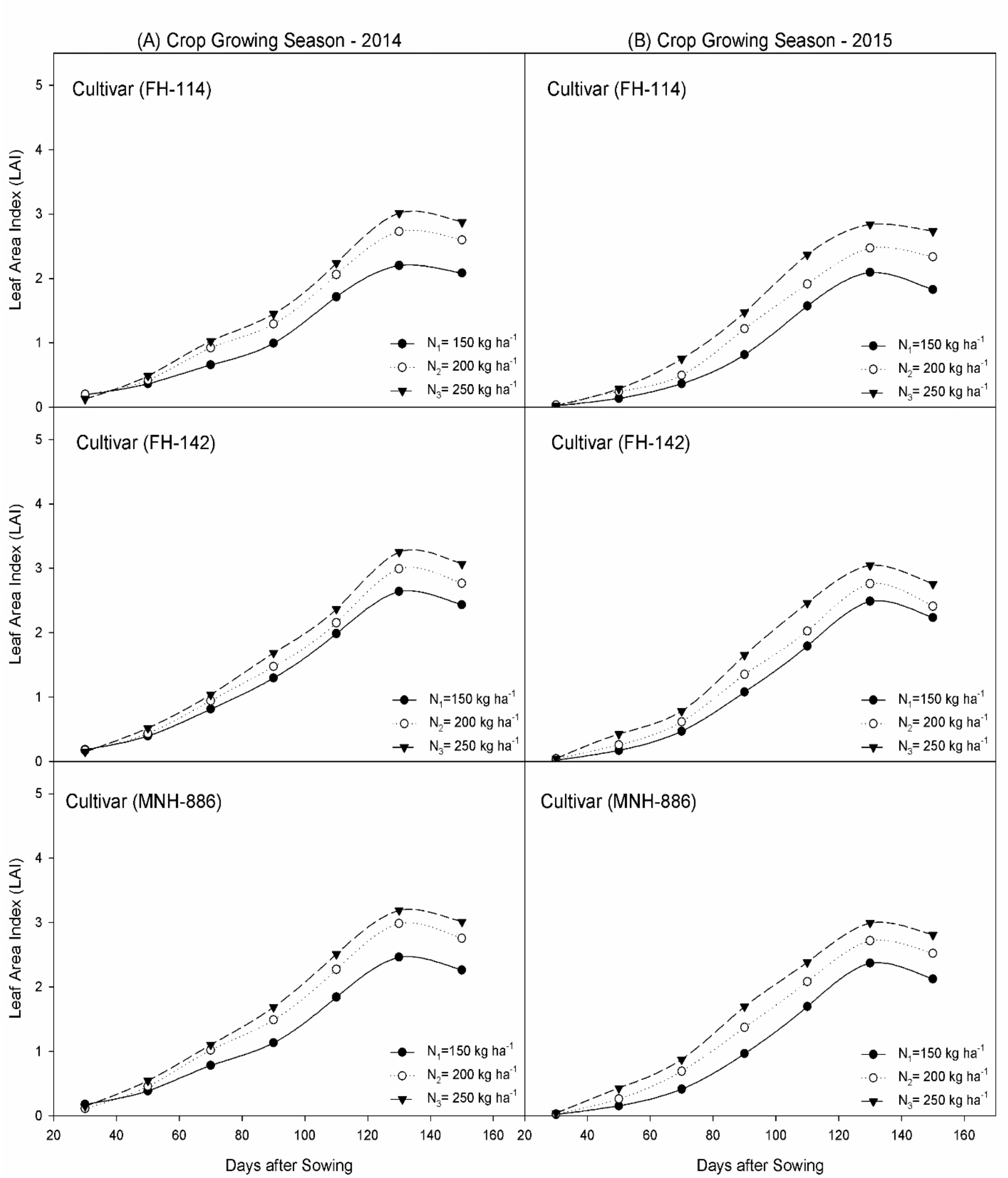

Figure 4.10: Time course change in leaf area index of different cultivars sown in the month of June at Multan during crop growing seasons of 2014 and 2015

4.3.2. Leaf Area Duration (days)

Significant differences were observed among sowing days for leaf area duration during both growing seasons. As dry matter accumulation increased during both years, leaf area duration also increased progressively till 130 days after sowing and then increased slowly. Data regarding leaf area duration (LAD) for different sowing dates, cultivars and nitrogen levels along-with its interaction at three locations (Faisalabad, Sahiwal and Multan) for two years (2014 and 2015) are presented in Table 4.8. Highly significant differences ($P<0.01$) were observed among sowing dates, cultivars and nitrogen rates during both growing seasons at all locations.

Leaf area duration was higher in May sown cotton while lower was recorded in June sown crop. On an average of all locations, maximum LAD (279.27 days) was recorded in May sown crop while minimum LAD (173.41 days) was recorded in June sown crop.

Variation in cultivars also existed due to different genotypic characteristics and leaf and canopy architecture differences. Higher LAD was recorded in cultivars FH-142 and MNH-886 and lower value of LAD was observed in cultivar FH-114 during both years at all locations. On an average, higher leaf area duration (232.46 days) was computed from FH-142 followed by MNH-886 (240.93 days) whereas lower LAD (205.62 days) was observed from FH-114.

Higher nitrogen generally increase dry matter accumulation and duration of leaf activeness as compared to its lower level. Experimental data revealed that nitrogen rate of 250 kg ha^{-1} showed maximum LAD (261.51 days) followed by 200 kg N ha^{-1} (232.38 days) and comparatively minimum LAD (185.13 days) was recorded where 150 kg N ha^{-1} was applied. Experimental results are similar to the findings of Wajid *et al*. (2010)

Interactive effects between sowing dates vs cultivars and among sowing dates, cultivars and nitrogen rates remained non-significant ($P>0.05$). Leaf area duration response to genotypes was modified by nitrogen rates at Sahiwal during both growing seasons (Table 4.9). FH-142 with 250 kg N ha^{-1} attained higher leaf area duration (295.82 days and 286.04 days) followed by MNH-886 which is statistically at par while FH-114 attained lower LAD (171.95 days and 162.08 days) during 2014 and 2015 respectively at Sahiwal.

Interaction among sowing dates and nitrogen rate was statistically significant during 2015 at Sahiwal (Table 4.10) and during 2014 at Multan (4.11). Crop sown in the month of May performed well and achieved higher LAD (329.40 days and 312.64 days) with nitrogen dose of 250 kg ha^{-1} as compared to crop sown in the month of June that produced lower LAD (121.88 days and 157.89 days) during 2015 at Sahiwal and 2014 at Multan respectively. Year effect was detected as non-significant.

Table 4.8: Leaf Area Duration (days) as affected by site, sowing date and nitrogen rate for three cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	309.56 A	274.92 A	282.51 A	287.18 A	270.50 A	250.99 A	279.27
SD_2= 1st June	181.06 B	164.55 B	182.72 B	156.08 B	187.97 B	168.09 B	173.41
HSD 5%	3.15	43.30	18.44	21.35	18.16	28.59	-
Significance	**	**	**	**	**	**	-
(B) Cultivar							
V_1 = FH-114	218.82 B	198.24 C	207.02 C	196.08 C	216.20 B	197.41 B	205.62
V_2 = FH-142	266.44 A	236.46 A	253.27 A	242.25 A	233.94 AB	213.27 A	240.93
V_3 = MNH-886	250.66 A	224.50 B	237.56 B	226.56 B	237.56 A	217.93 A	232.46
HSD 5%	18.11	11.88	14.35	11.38	18.47	9.10	-
Significance	**	**	**	**	*	**	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	196.93 C	181.36 C	189.28 C	176.54 C	192.59 C	174.08 C	185.13
N_2= 200 kg ha^{-1}	256.29 B	227.42 B	240.63 B	230.77 B	230.76 B	208.45 B	232.38
N_3= 250 kg ha^{-1}	282.70 A	250.41 A	267.94 A	257.57 A	264.35 A	246.09 A	261.51
HSD 5%	13.17	9.46	8.82	11.17	11.50	9.05	-
Significance	**	**	**	**	**	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	**	*	NS	-
B × C	NS	NS	*	*	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	245.31	219.73	232.62	221.63	229.23	209.54	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

Table 4.9: Interaction effect of cultivar and nitrogen rate on LAD (days) at Sahiwal

(A) 2014

Nitrogen Rate	**Cultivars**			**Mean**
	FH-114	**FH-142**	**MNH-886**	
150 kg ha^{-1}	171.95 g	204.13 f	191.75 fg	189.28
200 kg ha^{-1}	217.11 ef	259.87 bc	244.92 cd	240.63
250 kg ha^{-1}	232.00 de	295.82 a	276.00 ab	267.94
Mean	207.02	253.27	237.56	-
HSD 5%	20.79			-

Means sharing different letters differs significantly at $p \leq 0.05$

(B) 2015

Nitrogen Rate	**Cultivars**			**Mean**
	FH-114	**FH-142**	**MNH-886**	
150 kg ha^{-1}	162.08 g	189.75 f	177.79 fg	176.54
200 kg ha^{-1}	204.24 ef	250.97 bc	237.11 cd	230.77
250 kg ha^{-1}	221.91 de	286.04 a	264.78 ab	257.57
Mean	196.08	242.25	226.56	-
HSD 5%	26.32			-

Means sharing different letters differs significantly at $p \leq 0.05$

Table 4.10: Interaction between sowing dates and nitrogen rates affecting LAD (days) at Sahiwal during 2015

Nitrogen Rate	Cultivars		Mean
	1st May	1st June	
150 kg ha^{-1}	231.20 c	121.88 f	176.54
200 kg ha^{-1}	300.95 b	160.60 e	230.77
250 kg ha^{-1}	329.40 a	185.75 d	257.57
Mean	287.18	156.08	-
HSD 5%	19.55		-

Means sharing different letters differs significantly at $p \leq 0.05$

Table 4.11: Interaction between sowing dates and nitrogen rates affecting LAD at Multan during 2014

Nitrogen Rate	Cultivars		Mean
	1st May	1st June	
150 kg ha^{-1}	227.29 c	157.89 e	192.59
200 kg ha^{-1}	271.56 b	189.96 d	230.76
250 kg ha^{-1}	312.64 a	216.06 c	264.35
Mean	270.50	187.97	-
HSD 5%	20.14		-

Means sharing different letters differs significantly at $p \leq 0.05$

4.3.3. Total Dry Matter (kg ha^{-1})

Total dry matter (TDM) is the product of amount of solar radiation intercepted during growing season and its efficiency. Data regarding TDM for different sowing dates, cultivars and nitrogen levels along-with its interaction at three locations (Faisalabad, Sahiwal and Multan) for two years (2014 and 2015) are presented in Table 4.12. Sowing dates, cultivar differences and nitrogen treatments were highly significant ($P<0.01$) at three locations during both years of 2014 and 2015. However, Interactive effects between sowing dates vs cultivars, sowing dates vs nitrogen rates, cultivars vs nitrogen rates and among sowing dates, cultivars and nitrogen rates remained non-significant ($P>0.05$).

Higher biomass was produced in 2014 as compared to 2015 due to higher solar radiation and heat unit accumulation whereas, higher dry matter was observed at Sahiwal due to more sunshine hours as compared to other sites. Early sown crop produced more dry matter due to longer duration of crop and more accumulation of heat units whereas late sown crop produced less dry matter due to short duration of crop period. Crop sown on 1st May enhanced TDM over late sown 1st June by 31.80% vs 25.66% at Faisalabad, 33.60% vs 26.86% at Sahiwal and 29.40% vs 25.52% in both years. In June sowing, shorter time for vegetative growth and lower biomass accumulation resulted in inability to support high fruit load and crop quickly transferred to "cutout" that ultimately leads to reduced seed cotton yield (Bange and Milroy, 2000).

Cultivars significantly differed in dry matter accumulation and spreading type cultivars produced more dry matter in comparison with erect type cultivar. FH-142 accumulated higher dry matter at Faisalabad and Sahiwal while cultivar MNH-886 produced higher dry matter at Multan. Cultivar FH-142 significantly produced more TDM over other cultivars (FH-114 and MNH-886) by mean values of 11.42% and 2.31%. Cultivar FH-142 showed less potential in TDM production. Results are parallel to the findings of Wajid *et al*. (2010)

Higher nitrogen rate contributed towards more vegetative growth of plant and delay in transformation from vegetative to reproductive phase. Among nitrogen rates, 250 kg ha^{-1} remained statistically higher by 10.49% and 24.85% over 200 kg ha^{-1} and 150 kg ha^{-1} in TDM production. Results are in agreement with the findings of Hussein (2005); Wajid *et al*. (2010).

Figures 4.12 and 4.13 show time course changes in dry matter accumulation of three cotton cultivars sown in the month of May and June at Faisalabad. Pronounced effects were seen with 250 kg N ha^{-1} over other nitrogen rates. FH-142 performed best in dry matter production over other cultivars. Figure 4.14 and 4.15 showed time course change in dry matter production of different cultivars sown in the month of May and June at Sahiwal. Unequivocal effect had been seen with higher rate over lower nitrogen rates and TDM production by cultivar FH-142 was good over other cultivars. Figures 4.16 and 4.17 showed time course change in dry matter accumulation of different cultivars sown in the month of May and June at Multan. Pronounced effects have been seen with 250 kg N ha^{-1} the over other two nitrogen rates and performance of cultivar MNH-886 was remarkable in dry matter production over other cultivars.

Relationship between total dry matter and intercepted solar radiation for the season was positive and linear as shown below in Figure 4.11. Equation showed that 3.54 g m^{-2} dry matter was produced by utilizing 1 MJ of intercepted solar radiation and common regression accounted for 95% variation in the data.

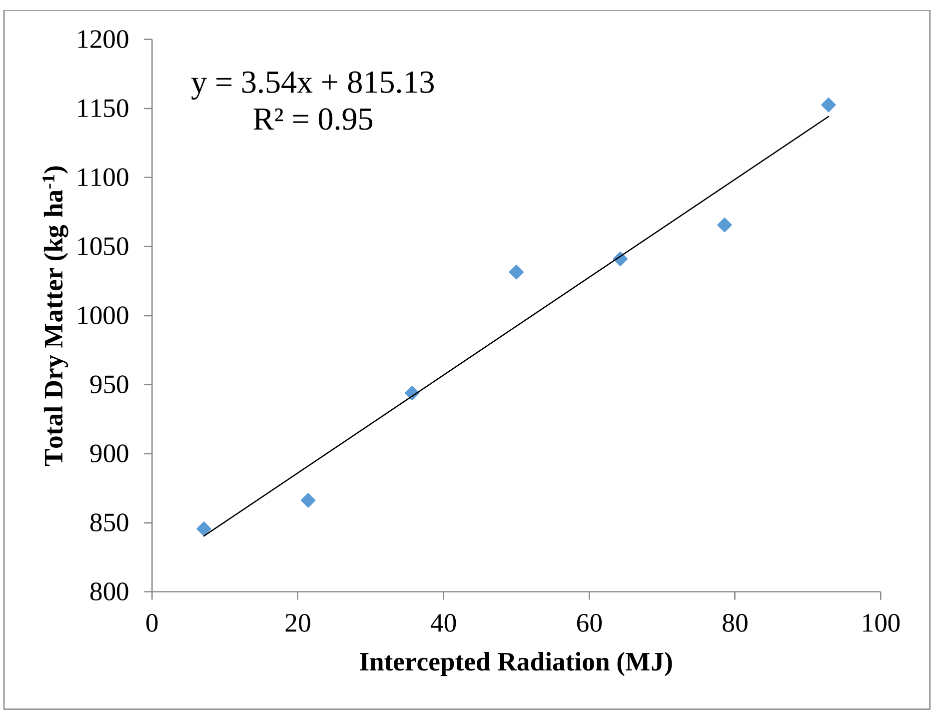

Figure 4.11: Relationship between total dry matter (kg ha^{-1}) and intercepted radiation (MJ).

Table 4.12: Total Dry Matter (kg ha^{-1}) as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	12575 A	11807 A	12145 A	11447 A	11869 A	11438 A	11880.16
SD_2= 1st June	8576 B	8777 B	8064 B	8372 B	8422 B	8518 B	8454.83
HSD 5%	1076.1	627.64	1430.2	1043.5	1923.1	706.74	-
Significance	**	**	**	**	*	**	-
(B) Cultivar							
V_1 = FH-114	9714 B	9405 B	9339 B	9140 B	9633 B	9396 B	9437.83
V_2 = FH-142	11250 A	11009 A	10715 A	10429 A	10305 AB	10226 AB	10655.66
V_3 = MNH-886	10762 AB	10462 A	10261 AB	10159 A	10499 A	10311 A	10409
HSD 5%	1396.6	743.71	1186	687.93	775.75	894.25	-
Significance	*	**	*	**	*	*	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	9088 C	8640 C	8826 C	8316 C	8630 C	8468 C	8661.33
N_2= 200 kg ha^{-1}	10879 B	10680 B	10298 B	10086 B	10048 B	9902 B	10315.50
N_3= 250 kg ha^{-1}	11758 A	11556 A	11191 A	11327 A	11757 A	11563 A	11525.66
HSD 5%	613.04	627.11	573.52	521.04	546.62	504.98	-
Significance	**	**	**	**	**	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	10575	10292	10105	9909.6	10146	9945.7	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

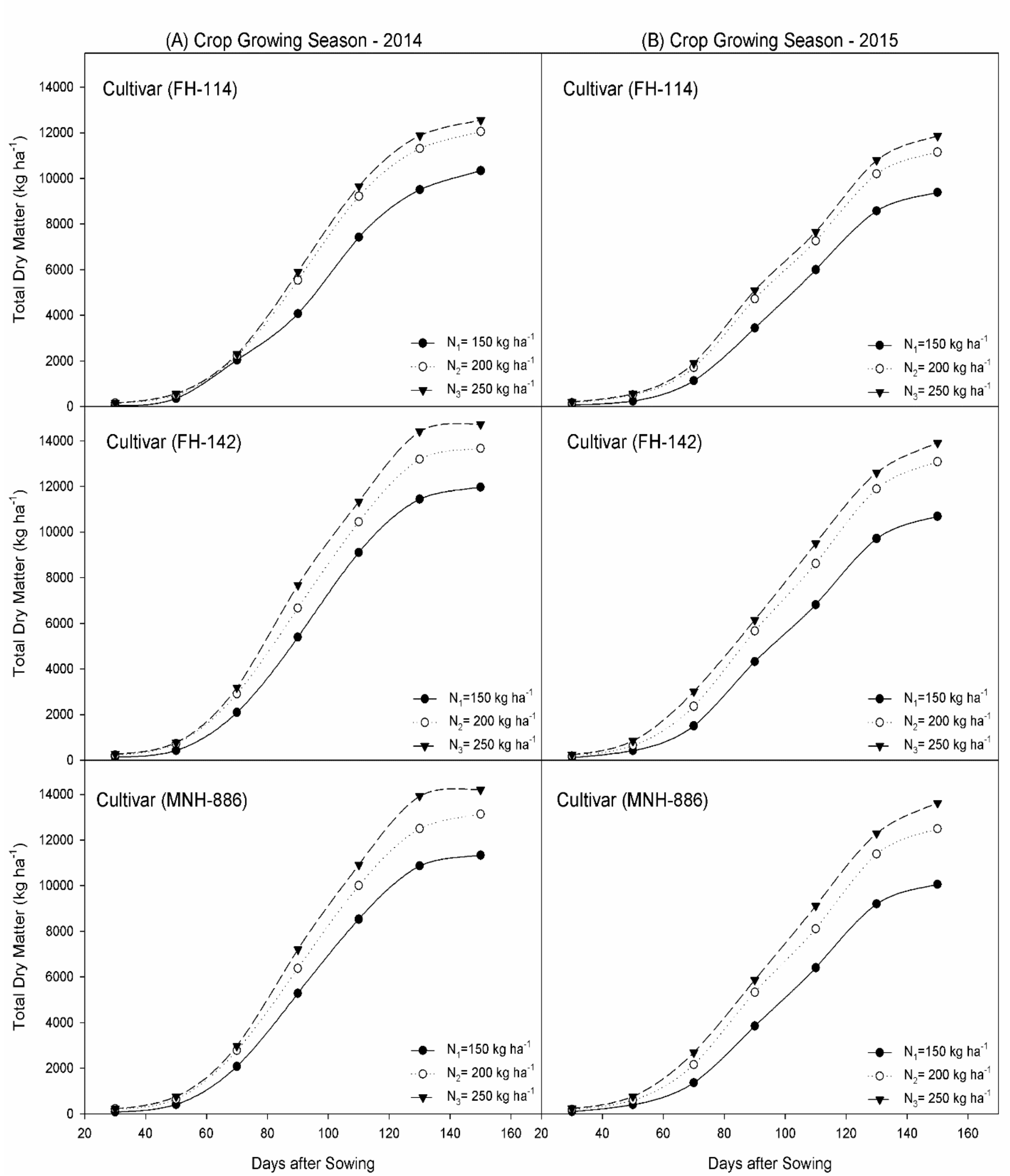

Figure 4.12: Time course change in total dry matter (kg ha^{-1}) of different cultivars sown in the month of May at Faisalabad during crop growing seasons of 2014 and 2015.

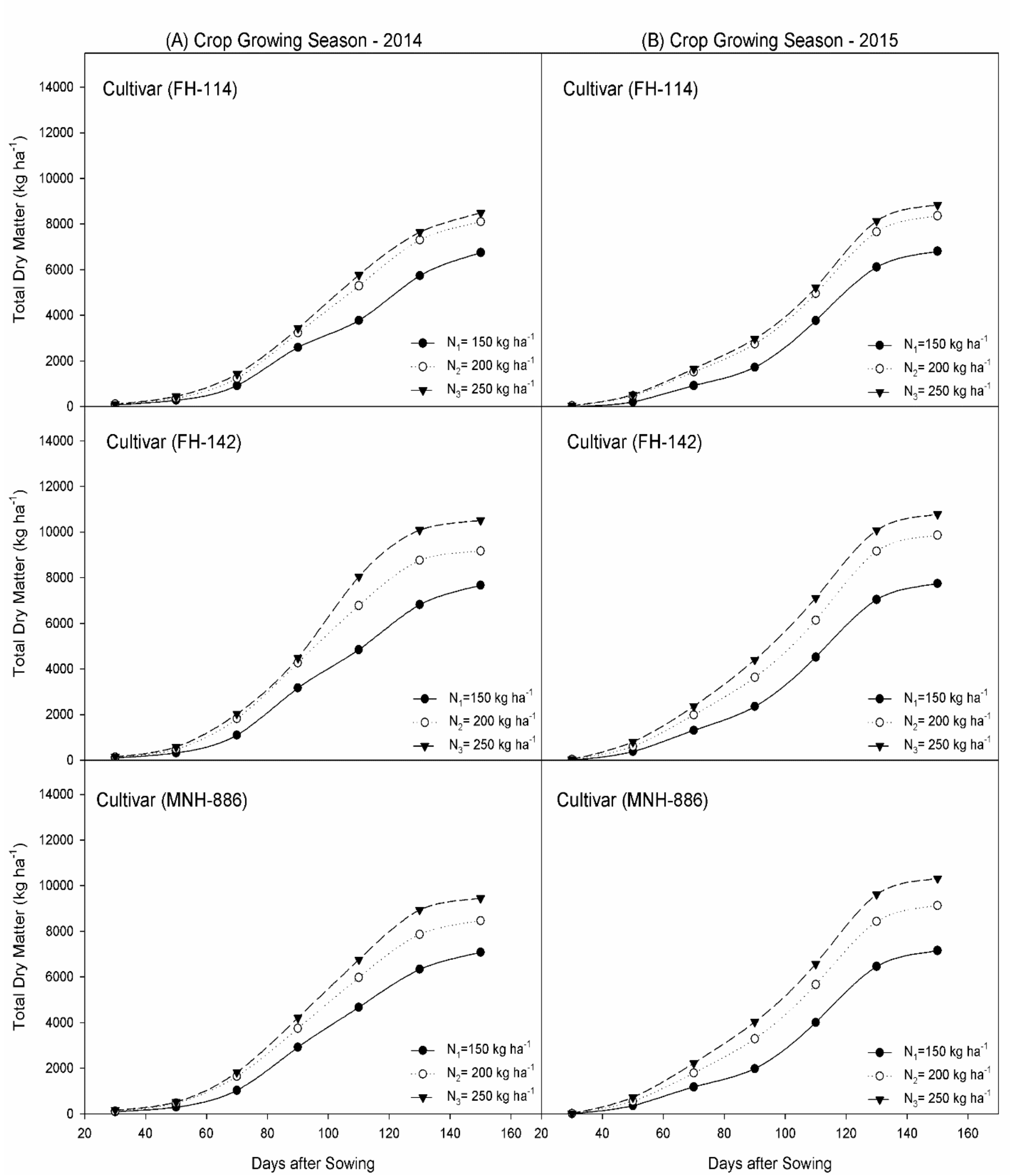

Figure 4.13: Time course change in total dry matter (kg ha^{-1}) of different cultivars sown in the month of June at Faisalabad during crop growing seasons of 2014 and 2015.

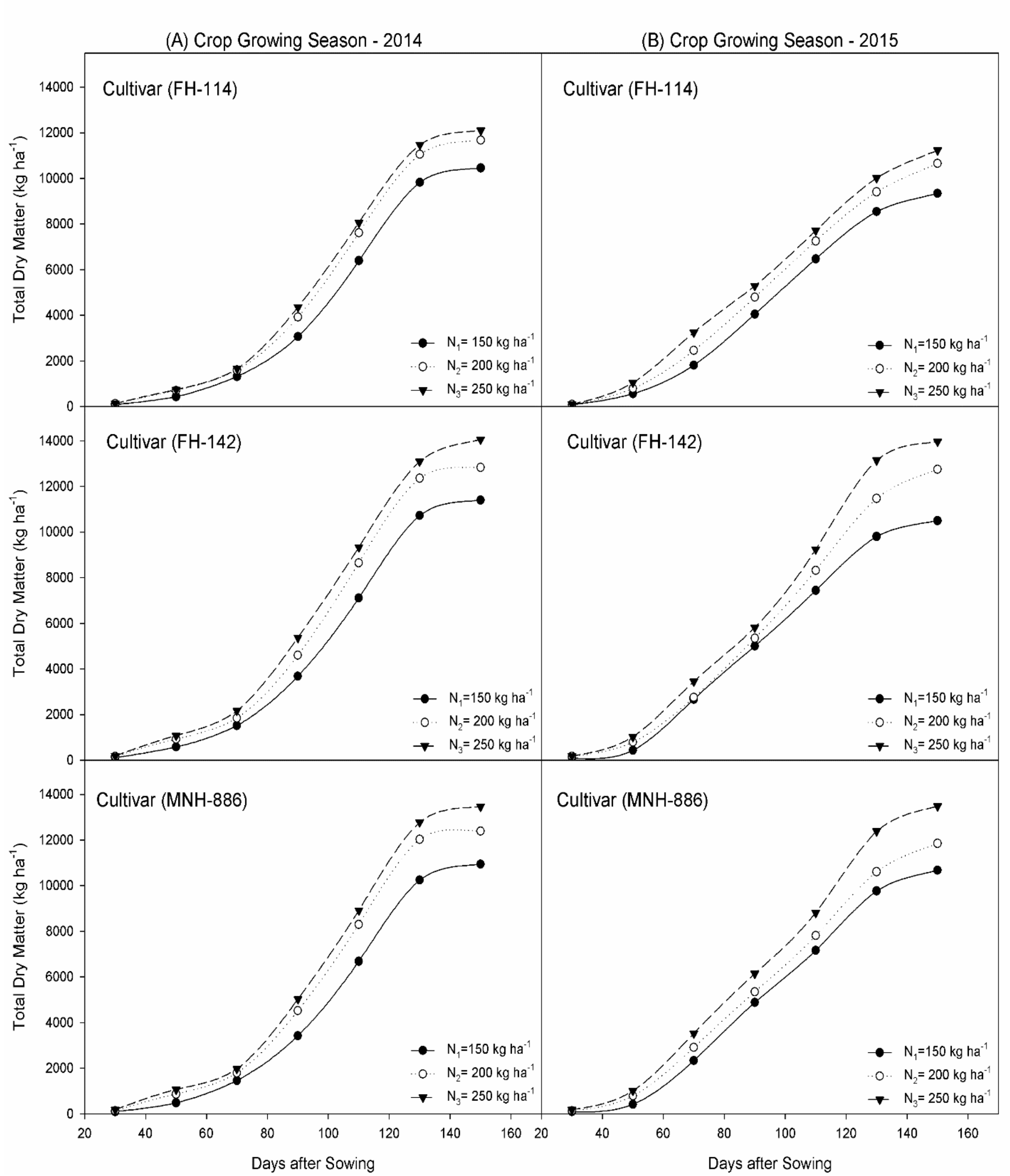

Figure 4.14: Time course change in total dry matter (kg ha^{-1}) of different cultivars sown in the month of May at Sahiwal during crop growing seasons of 2014 and 2015.

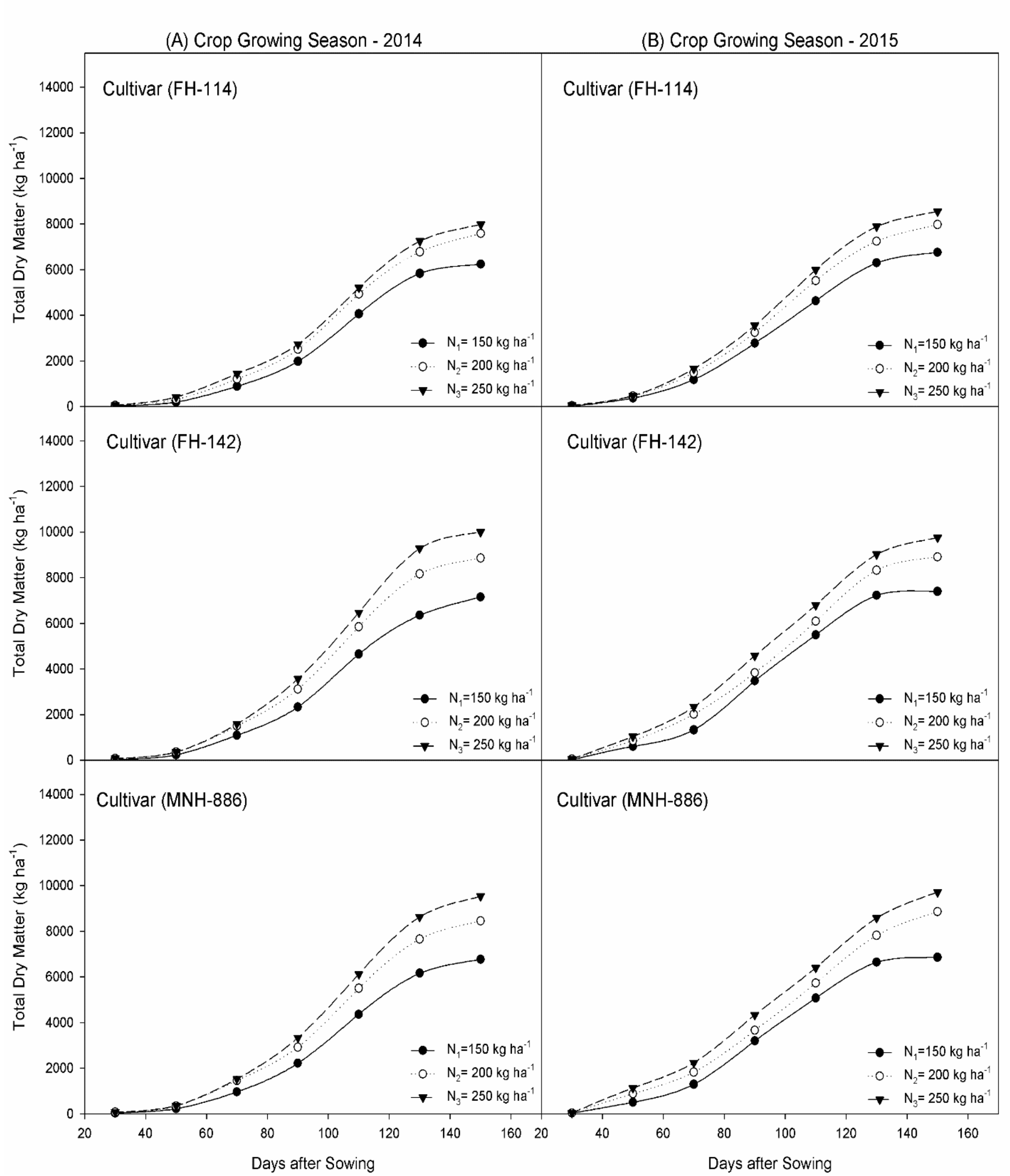

Figure 4.15: Time course change in total dry matter (kg ha^{-1}) of different cultivars sown in the month of June at Sahiwal during crop growing seasons of 2014 and 2015.

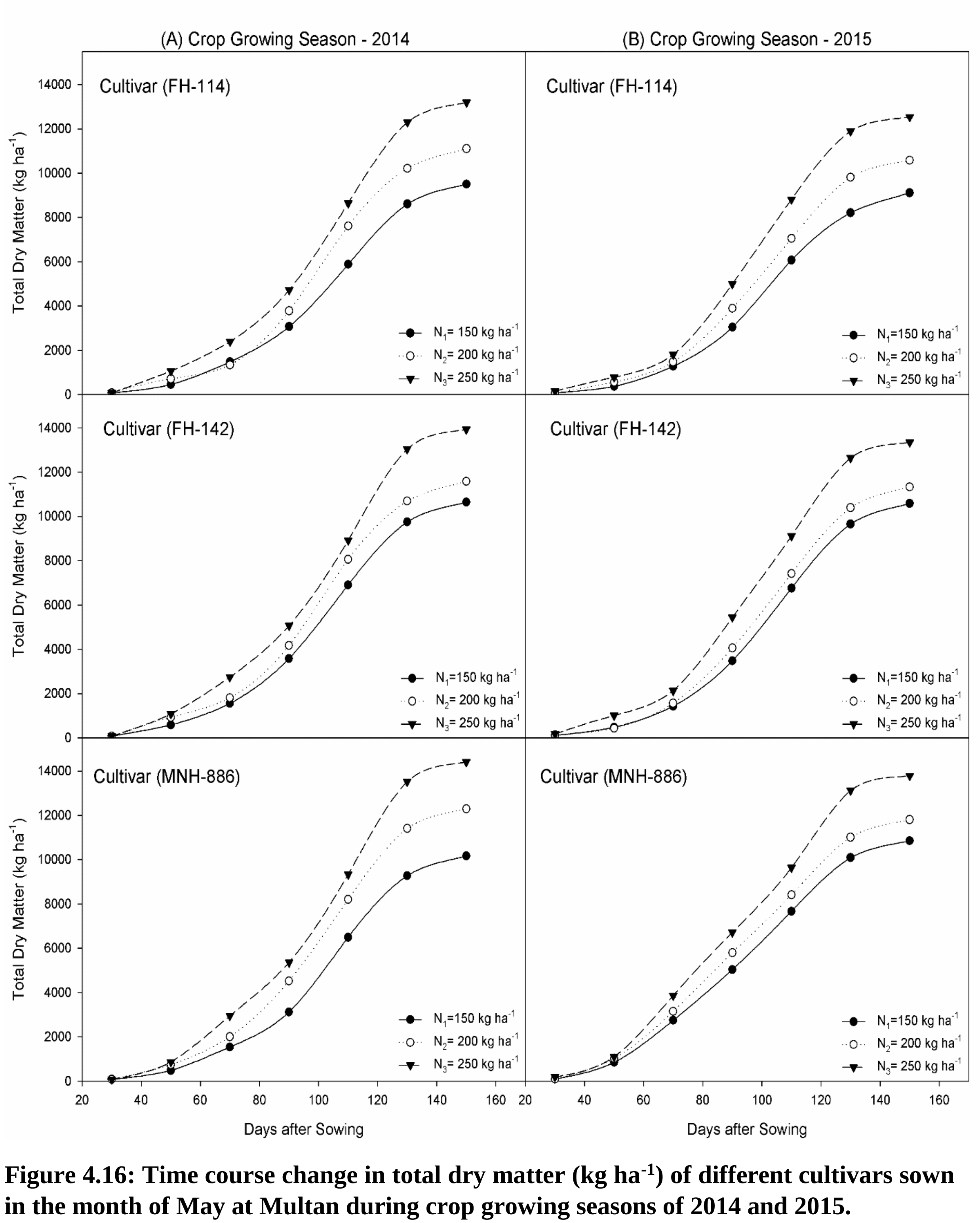

Figure 4.16: Time course change in total dry matter (kg ha^{-1}) of different cultivars sown in the month of May at Multan during crop growing seasons of 2014 and 2015.

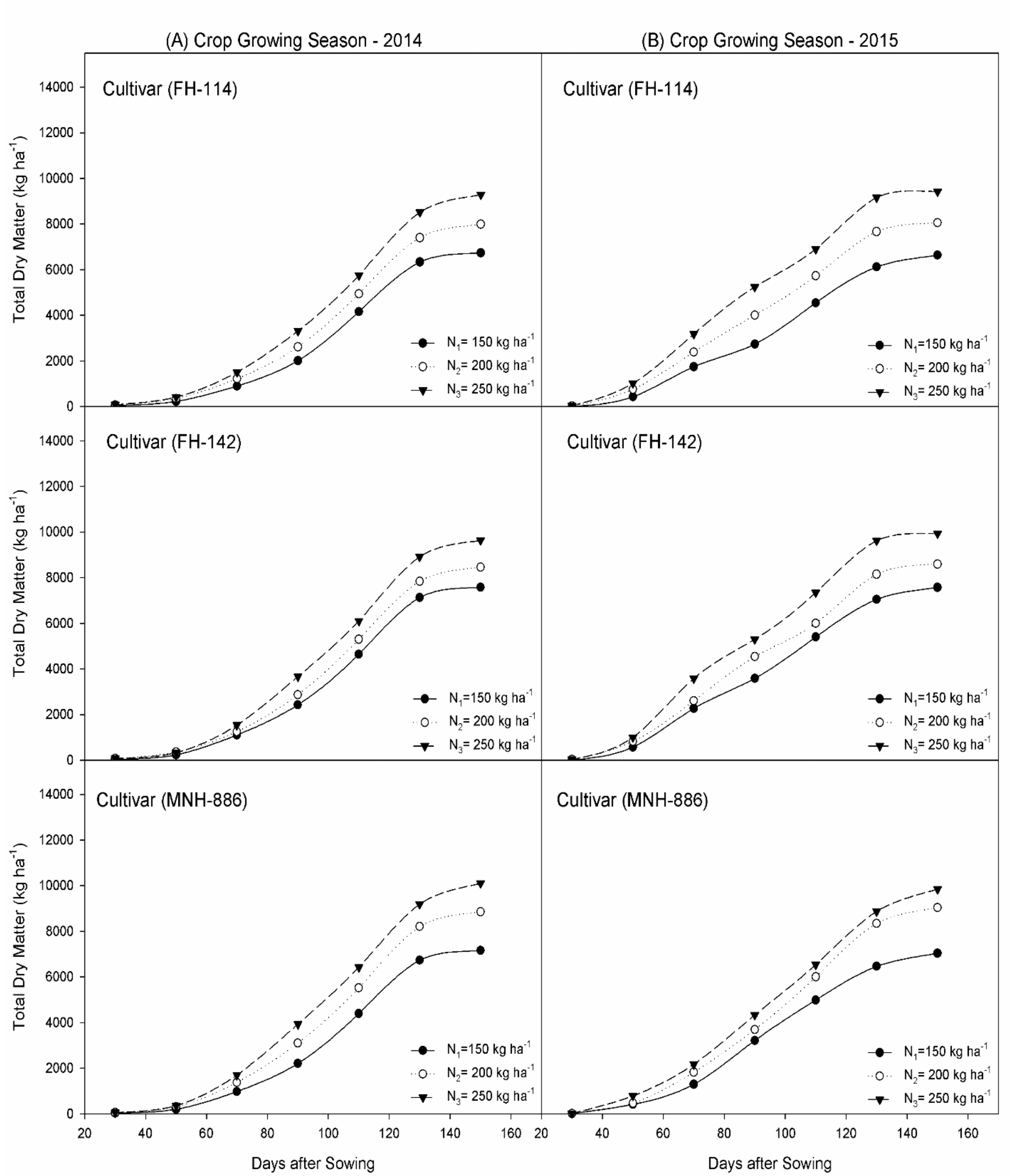

Figure 4.17: Time course change in total dry matter (kg ha^{-1}) of different cultivars sown in the month of June at Multan during crop growing seasons of 2014 and 2015.

4.3.4. Crop growth rate (g m^{-2} day^{-1})

Crop growth rate is the production of dry matter per day. Data regarding CGR for different sowing dates, cultivars and nitrogen levels along-with its interaction at three locations (Faisalabad, Sahiwal and Multan) for two years (2014 and 2015) are presented in Table 4.13. Sowing dates, cultivar differences and nitrogen treatments were highly significant ($P<0.01$) at three locations during both years of 2014 and 2015. However, Interactive effects between sowing dates vs cultivars, sowing dates vs nitrogen rates, cultivars vs nitrogen rates and among sowing dates, cultivars and nitrogen rates remained non-significant ($P>0.05$). Year effect was also observed as non-significant.

Sowing dates significantly affected mean crop growth rate. Higher crop growth was observed in May sown crop during growing season of 2014 as compared to 2015 at all locations. May sown crop showed higher crop growth rates of 31.9% and 24.8% at Faisalabad, 33.3% and 26.4% at Sahiwal, and 14.3% and 25% at Multan in 2014 and 2015, respectively due to favorable climatic conditions as compared to June sown crop. Experimental findings are supported by Reddy *et al*. (2005) and Singh *et al*. (2007).

Cultivars also showed significant differences in mean CGR during both growing season at all locations expect at Multan where CGR was non-significant during 2015 and this also depends on efficient utilization of solar radiation. Maximum value of mean CGR was computed from cultivar FH-142 which was at par with cultivar MNH-886 at Faisalabad and Sahiwal. At Multan site, cultivar MNH-886 performed well with high efficiency and achieved maximum value of mean CGR which was at par with cultivar FH-142. Minimum value of CGR was computed from cultivar FH-114 at all locations. On an average of all locations, cultivar FH-142 attained maximum CGR (8.78 g m^{-2} day^{-1}) followed by MNH-886 and minimum CGR (7.80 g m^{-2} day^{-1}) was observed from cultivar FH-114. Similar trend was shown by all cultivars during both growing season (2014 and 2015).

Nitrogen application directly related to vegetative growth and it contributed higher total dry matter accumulation. Higher dose of nitrogen significantly enhanced mean CGR at all locations during both growing seasons. On an average, mean CGR at 150, 200 and 250 kg N ha^{-1} was 7.17, 8.52 and 9.51 gm^{-2} day^{-1}, respectively.

Table 4.13: Crop Growth Rate (g m^{-2} day^{-1}) as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	10.34 A	9.70 A	10.00 A	9.43 A	9.82 A	9.46 A	9.79
SD_2= 1st June	7.04 B	7.29 B	6.67 B	6.94 B	6.98 B	7.11 B	7.01
HSD 5%	0.90	0.50	1.1879	0.89	1.59	0.60	-
Significance	**	**	**	**	*	**	-
(B) Cultivar							
V_1 = FH-114	8.00 B	7.76 B	7.71 B	7.55 B	7.97 B	7.80 B	7.80
V_2 = FH-142	9.23 A	9.08 A	8.83 A	8.61 A	8.53 AB	8.39 AB	8.78
V_3 = MNH-886	8.84 AB	8.64 A	8.46 AB	8.39 A	8.69 A	8.67 A	8.62
HSD 5%	1.17	0.61	0.99	0.56	0.64	0.74	-
Significance	*	**	*	**	*	*	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	7.49 C	7.15 C	7.29 C	6.88 C	7.14 C	7.05 C	7.17
N_2= 200 kg ha^{-1}	8.93 B	8.81 B	8.49 B	8.33 B	8.32 B	8.23 B	8.52
N_3= 250 kg ha^{-1}	9.64 A	9.52 A	9.22 A	9.35 A	9.74 A	9.58 A	9.51
HSD 5%	0.52	0.52	0.47	0.43	0.45	0.42	-
Significance	**	**	**	**	**	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	8.69	8.49	8.33	8.18	8.40	8.22	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.3.5. Net assimilation rate (g m^{-2} day^{-1})

Growth rates are fundamentally important for crop growth analysis. According to Hunt (1978), net assimilation rate (NAR) of any crop is the photosynthetically efficient dry weight production per unit leaf area duration. Data regarding CGR for different sowing dates, cultivars and nitrogen levels along-with its interaction at three locations (Faisalabad, Sahiwal and Multan) for two years (2014 and 2015) are presented in Table 4.14. Sowing dates, cultivar differences and nitrogen treatments were significant ($P<0.05$) at three locations during both years of 2014 and 2015. However, Interactive effects between sowing dates vs cultivars, sowing dates vs nitrogen rates, cultivars vs nitrogen rates and among sowing dates, cultivars and nitrogen rates remained non-significant ($P>0.05$). Year effect was also observed as non-significant.

Sowing dates significantly affected net assimilation rate at all locations during both growing seasons. The late sowing in the month of June increased NAR over early sowing in the month of May. On an average of all locations, June sown crop attained an almost 20% higher NAR (5.22 g m^{-2} day^{-1}) in comparison with May sown crop where NAR was less (4.18 g m^{-2} day^{-1}).

Net assimilation rates of the three cultivars did not differ significantly for all locations during both growing seasons whereas a significant trend was observed at Sahiwal during the second year of the experiment only. Maximum NAR (4.99 g m^{-2} day^{-1}) was recorded from cultivar FH-114 whereas minimum NAR (4.48 g m^{-2} day^{-1}) was observed from cultivar FH-142.

NAR was strongly and positively associated with area-based photosynthetic rate and leaf nitrogen content (Li *et al*., 2016). Application of different doses of nitrogen significantly affected NAR at Faisalabad and Sahiwal during first year of experiment while a non-significant trend was observed at other location. A negative relationship was observed with different rates of nitrogen. Net assimilation rate was lower at higher dose of nitrogen while higher at lower dose of nitrogen. Less vegetative growth was observed due to less nitrogen rate that ultimately leads to lower crop canopy and more photosynthesis rate. According to Hunt (1978), variation in average NAR indicates that differences in yield over a range environment are likely to be determined by differences in LAD.

Table 4.14: Net Assimilation Rate (g m^{-2} day^{-1}) as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	4.08 B	4.30 B	4.34 B	4.01 B	4.30 B	4.05 B	4.18
SD_2= 1st June	4.83 A	5.38 A	5.27 A	5.46 A	5.30 A	5.10 A	5.22
HSD 5%	0.38	0.49	0.73	0.97	0.97	0.74	-
Significance	*	*	*	*	*	*	-
(B) Cultivar							
V_1 = FH-114	4.60	4.94	4.95	4.99 A	4.84	4.62	4.82
V_2 = FH-142	4.33	4.78	4.68	4.48 B	4.77	4.59	4.60
V_3 = MNH-886	4.44	4.80	4.78	4.73 AB	4.79	4.52	4.68
HSD 5%	-	-	-	0.40	-	-	-
Significance	NS	NS	NS	*	NS	NS	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	4.79 A	4.98	5.11 A	4.97	4.87	4.70	4.90
N_2= 200 kg ha^{-1}	4.34 B	4.82	4.71 B	4.59	4.72	4.57	4.63
N_3= 250 kg ha^{-1}	4.23 B	4.72	4.59 B	4.64	4.81	4.45	4.58
HSD 5%	0.39	-	0.35	-	-	-	-
Significance	**	NS	**	NS	NS	NS	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	4.46	4.84	4.80	4.74	4.80	4.58	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.4. YIELD AND YIELD COMPONENTS

4.4.1. Number of opened bolls per plant

Data regarding number of opened bolls per plant for different sowing dates, cultivars and nitrogen levels along-with its interaction at three locations (Faisalabad, Sahiwal and Multan) for two years (2014 and 2015) are presented in Table 4.15. Sowing dates, cultivar differences and nitrogen treatments were highly significant ($P<0.01$) at three locations during both years of 2014 and 2015. However, Interactive effects between sowing dates vs cultivars, sowing dates vs nitrogen rates, cultivars vs nitrogen rates and among sowing dates, cultivars and nitrogen rates remained non-significant ($P>0.05$). Year analysis showed a non-significant relationship between first and second year.

Sowing dates significantly affected number of matured or opened bolls per plant. Maximum number of opened bolls per plant was obtained from May sown crop. Delay in crop sowing reduced number of opened bolls per plant due to less accumulation of heat units as compared to early sown crop. Experimental data revealed May sown crop produced more number of opened bolls (28). Comparatively, less number of opened bolls (18) were produced by June sown crop. These results are similar to findings of Arshad *et al*. (2007).

Cultivars significantly differed in producing number of matured bolls per plant and it depended on genetics and environmental conditions (Table 4.15). Early maturing cultivar (FH-114) produced more number of opened bolls however boll weight also less in that case. On an average of all locations, cultivar FH-114 produced higher number of opened bolls (25) which was significantly more in number than medium maturing cultivars i.e. MNH-886 (22) and FH-142 (19).

Nitrogen rates also influenced number of opened bolls per plant. Higher dose of nitrogen produced more number of matured bolls per plant and more transfer of assimilates to harvestable part. Comparatively, less number of matured bolls produced where lower dose of nitrogen fertilizer was applied. Nitrogen rate of 250 kg ha^{-1} conquered higher number (25.20) of opened bolls per plant whereas lower number (21.68) of opened bolls per plant were attained where nitrogen rate of 150 kg ha^{-1} was applied on an average of all locations.

Table 4.15: Number of opened bolls per plant as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	27.92 A	25.92 A	33.51 A	26.88 A	29.00 A	28.66 A	28.65
SD_2= 1st June	17.63 B	17.14 B	20.63 B	19.10 B	18.85 B	18.74 B	18.68
HSD 5%	5.53	7.74	6.52	1.89	4.0072	3.50	-
Significance	*	*	*	**	**	**	-
(B) Cultivar							
V_1 = FH-114	24.87 A	23.53 A	29.03 A	25.22 A	25.35 A	25.85 A	25.64
V_2 = FH-142	21.85 B	20.55 B	26.13 B	23.18 A	24.14 AB	23.48 B	23.22
V_3 = MNH-886	21.61 B	20.51 B	26.05 B	20.57 B	22.27 B	21.77 B	22.13
HSD 5%	2.0356	2.1652	2.1902	2.2407	2.0329	2.2405	-
Significance	**	**	**	**	**	**	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	21.09 B	19.75 B	25.25 B	20.03 C	21.25 C	20.61 B	21.68
N_2= 200 kg ha^{-1}	24.27 A	23.22 A	27.38 AB	23.42 B	24.16 B	24.33 A	24.46
N_3= 250 kg ha^{-1}	22.96 AB	21.63 AB	28.57 A	25.52 A	26.35 A	26.16 A	25.20
HSD 5%	3.13	3.02	2.91	1.44	1.91	1.89	-
Significance	*	*	*	**	**	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	22.77	21.53	27.07	22.99	23.92	23.70	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.4.2. Total number of bolls per plant

Data regarding total number of bolls per plant for different sowing dates, cultivars and nitrogen levels along-with its interaction at three locations (Faisalabad, Sahiwal and Multan) for two years (2014 and 2015) are presented in Table 4.16. Interactive effects between sowing dates vs cultivars, sowing dates vs nitrogen rates, cultivars vs nitrogen rates and among sowing dates, cultivars and nitrogen rates remained non-significant ($P>0.05$). Year analysis showed a non-significant relationship between first and second year.

Sowing dates significantly affected total number of bolls produced on plant. Maximum number of bolls per plant was obtained from May sown crop. Delay in crop sowing reduced number of opened bolls per plant. Experimental data revealed May sown crop produced more number of bolls (32.31). Comparatively, less number of bolls (21.10) were produced by June sown crop. These results are similar to findings of Arshad *et al*. (2007).

Cultivars non-significantly differed in producing number of bolls per plant at Faisalabad and Sahiwal which have similar environmental conditions. Cultivars FH-142 produced significantly more number of bolls during both growing seasons. Experimental results depicted that cultivar FH-142 produced higher number of bolls (28.85 and 28.51) which was significantly higher in number than cultivars FH-114 (28.40 and 28.07) and MNH-886 (26.37 and 26.03) during 1st and 2nd year at Multan.

Nitrogen rates also influenced total number of bolls per plant. Higher dose of nitrogen produced more number of bolls per plant. Comparatively, less number of bolls produced where lower dose of nitrogen fertilizer was applied. Nitrogen rate of 250 kg ha^{-1} conquered higher number (28.81) of bolls per plant whereas lower number (24.16) of bolls per plant were attained where nitrogen rate of 150 kg ha^{-1} was applied on an average of all locations.

Table 4.16: Total number of bolls per plant as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	32.37 A	30.25 A	38.29 A	28.61 A	34.22 A	30.12 A	32.31
SD_2= 1st June	19.32 B	19.17 B	23.32 B	22.43 B	21.5 B	20.86 B	21.10
HSD 5%	6.60	8.15	3.96	1.49	4.94	6.05	-
Significance	*	*	**	**	**	*	-
(B) Cultivar							
V_1 = FH-114	26.61	25.38	31.44	26.74	28.40 AB	28.07 AB	27.77
V_2 = FH-142	26.05	24.83	31.00	25.06	28.85 A	28.51 A	27.38
V_3 = MNH-886	24.87	23.92	29.98	24.76	26.37 B	26.03 B	25.99
HSD 5%	-	-	-	-	2.20	2.27	-
Significance	NS	NS	NS	NS	*	*	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	23.03 B	21.81 B	27.87 B	23.21 B	24.68 B	24.35 B	24.16
N_2= 200 kg ha^{-1}	27.35 A	26.40 A	31.13 A	26.81 A	28.85 A	28.51 A	**28.17**
N_3= 250 kg ha^{-1}	27.14 A	25.92 A	33.42 A	26.54 A	30.09 A	29.75 A	**28.81**
HSD 5%	3.34	3.22	3.00	3.20	3.19	3.09	-
Significance	**	**	**	*	**	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	25.846	24.716	30.809	25.526	27.877	27.03	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.4.3. Average boll weight (g)

Data regarding average boll weight for different sowing dates, cultivars and nitrogen levels along-with its interaction at three locations (Faisalabad, Sahiwal and Multan) for two years (2014 and 2015) are presented in Table 4.17. Interactive effects between sowing dates vs cultivars, sowing dates vs nitrogen rates, cultivars vs nitrogen rates and among sowing dates, cultivars and nitrogen rates remained non-significant ($P>0.05$). Statistically non-significant trend was observed in year analysis.

Cotton boll weight is another important parameter to define crop yield. Sowing dates significantly affected average boll weight. Early sown crop utilized more solar radiation and heat units in later stage to produce higher boll weight during both growing seasons at all locations. Experimental data of all locations showed that average boll weight of May sown crop was higher (3.25 g) than late sown crop (2.66 g).

Significant differences were observed among cultivars for average boll weight. Variations in boll weight depends on genetic characteristics of relevant cultivar as well. Cultivar FH-142 performed well at all locations during both growing seasons. Although total number of bolls per plant were higher on FH-114, however average boll weight was lower for this cultivar. Overall average bases, it is clear that FH-142 produced higher boll weight (3.24 g) followed by MNH-886 (3.08 g) and less boll weight (2.53 g) was produced by cultivar FH-114 during both growing seasons.

Nitrogen rates significantly affected boll weight. Maximum boll weight was produced with higher dose of nitrogen. Experimental results from all locations depicted that nitrogen dose of 250 kg ha^{-1} produced maximum boll weight (3.11 g) and lower nitrogen rate of 150 kg N ha^{-1} produced minimum boll weight (2.78 g).

Table 4.17: Average boll weight (g) as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	3.25 A	3.00 A	3.34 A	3.32 A	3.33 A	3.26 A	3.25
SD_2= 1st June	2.76 B	2.48 B	2.49 B	2.83 B	2.84 B	2.54 B	2.66
HSD 5%	0.32	0.39	0.82	0.48	0.39	0.38	-
Significance	*	*	*	*	*	*	-
(B) Cultivar							
V_1 = FH-114	2.59 B	2.34 B	2.59 B	2.50 B	2.68 B	2.49 B	2.53
V_2 = FH-142	3.29 A	3.01 A	3.42 A	3.20 A	3.37 A	3.19 A	3.24
V_3 = MNH-886	3.13 A	2.86 A	3.21 A	3.04 A	3.21 A	3.03 A	3.08
HSD 5%	0.29	0.28	0.29	0.28	0.30	0.27	-
Significance	**	**	**	**	**	**	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	2.83 B	2.57 B	2.88 B	2.74 B	2.91 B	2.73 B	2.78
N_2= 200 kg ha^{-1}	3.04 A	2.77 A	3.11 A	2.95 A	3.12 A	2.94 A	2.99
N_3= 250 kg ha^{-1}	3.14 A	2.87 A	3.23 A	3.15 A	3.23 A	3.04 A	3.11
HSD 5%	0.20	0.19	0.21	0.20	0.20	0.2	-
Significance	**	**	**	**	**	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	3.00	2.74	3.03	2.96	3.09	2.90	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.4.4. Seed index (g)

Seed index (SI) or 100-seed weight is also an important yield factor and plays imperative role in increasing seed cotton yield. Data regarding seed index for different sowing dates, cultivars and nitrogen levels along-with its interaction at three locations (Faisalabad, Sahiwal and Multan) for two years (2014 and 2015) are presented in Table 4.18. Interactive effects between sowing dates vs cultivars, sowing dates vs nitrogen rates, cultivars vs nitrogen rates and among sowing dates, cultivars and nitrogen rates remained non-significant ($P>0.05$). Year analysis showed a non-significant trend.

Table 4.18 showed that a statistically non-significant trend was observed for sowing dates at all locations during 1st year of experiment while in 2015, significant difference among sowing dates was observed at Sahiwal where higher 100-seed weight (6.90 g) was observed in May sown as compared to June sown crop (6.47 g).

Cultivars were significantly differed in 100-seed weight. Maximum 100-seed weight was observed from cultivar MNH-886 followed by cultivar FH-142 while minimum 100-seed weight was observed from cultivar FH-114. On an average, maximum SI (7.12 g) was observed from MNH-886 and minimum SI (5.86 g) was observed from FH-142. Results are supported by Iqbal (2011) and Singh *et al*. (2009) and they reported that varieties differ in seed index.

Nitrogen rates did not significantly affect 100-seed weight at all locations except 2nd year experiment at Sahiwal where maximum weight of 100-seeds (6.90 g) was recorded at nitrogen dose of 150 kg ha^{-1} during 2015.

Table 4.18: Seed index (g) as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	7.13	6.83	7.26	6.90 A	7.14	6.88	7.03
SD_2= 1st June	6.76	6.36	6.11	6.47 B	6.78	6.59	6.51
HSD 5%	-	-	-	0.32	-	-	-
Significance	NS	NS	NS	*	NS	NS	-
(B) Cultivar							
V_1 = FH-114	6.35 B	5.99 B	6.09 B	6.07 B	6.39 B	6.18 B	6.18
V_2 = FH-142	7.13 A	6.86 A	6.87 A	6.93 AB	7.23 A	6.98 A	5.86
V_3 = MNH-886	7.36 A	6.93 A	7.10 A	7.04 A	7.26 A	7.05 A	7.12
HSD 5%	0.78	0.75	0.74	0.94	0.72	0.71	-
Significance	*	*	*	*	*	*	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	7.05	6.73	6.79	6.90 A	6.98	6.80	6.92
N_2= 200 kg ha^{-1}	6.93	6.54	6.67	6.68 B	6.99	6.73	6.75
N_3= 250 kg ha^{-1}	6.86	6.50	6.59	6.46 B	6.91	6.67	6.65
HSD 5%	-	-	-	0.22	-	-	-
Significance	NS	NS	NS	**	NS	NS	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	6.95	6.59	6.68	6.68	6.96	6.73	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.4.5. Seed cotton yield (kg ha^{-1})

Data regarding seed cotton yield for different sowing dates, cultivars and nitrogen levels along-with its interaction at three locations (Faisalabad, Sahiwal and Multan) for two years (2014 and 2015) are presented in Table 4.19. Sowing dates, cultivar differences and nitrogen treatments were highly significant ($P<0.01$) at all locations for both years of 2014 and 2015. However, Interactive effects between sowing dates vs cultivars, sowing dates vs nitrogen rates, cultivars vs nitrogen rates and among sowing dates, cultivars and nitrogen rates remained non-significant ($P>0.05$). Year analysis showed a non-significant relationship between first and second year.

Experimental data revealed that May sowing significantly enhanced seed cotton yield compared to June sowing at all locations for both years. On an average, seed cotton yield was 43% higher in May sown crop than June sown crop. This may be due to longer growing period of cotton along-with more sunshine hours availability and good crop establishment under mild temperature of early season. Similar results were reported by Arain *et al*. (2001), Bauer and Roof (2004) and Ali *et al*. (2004). They concluded that higher cotton production was achieved when crop was sown from 15th of April to 1st May.

Yield is regulated by genetics of cultivar and its environment that play role in partitioning of assimilates. The balance between vegetative and productive phase is very critical in case of cotton. This balance is influenced by management practices and other environmental factors. More vegetative growth can lead to late crop maturity. Cultivar differences in seed cotton yield were also significant and varied for all locations. At Faisalabad and Sahiwal, cultivar FH-142 produced maximum seed cotton yield and at Multan, cultivar MNH-886 produced highest seed cotton yield, whereas cultivar FH-114 produced the less seed cotton yield at all locations. It is because, FH-142 is developed by Cotton Research Station at Faisalabad which showed higher RUE_{YIELD} at Faisalabad and Sahiwal as compared to MNH-886 whereas MNH-886 developed by Cotton Research Station at Multan which showed higher RUE_{YIELD} at Multan as compared to FH-142. Mean value of seed cotton yield for cultivar FH-142 was 17.5% and 10% higher than other cultivars (FH-114 and MNH-886).

Different levels of nitrogen significantly affected seed cotton yield at all locations. Higher doses of nitrogen increased crop yield its optimum level and then yields decreased. Optimum level of nitrogen at rate of 200 kg ha^{-1} increased seed cotton yield by mean value of 1.17% and 15.84% compared to highest and lowest nitrogen level. The present studies corroborate the findings of other studies (Ali *et al*.,2004, Arshad, 2006; Hussain, 2006; and Shabbir, 2007).

Table 4.19: Seed cotton yield (kg ha^{-1}) as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	3427.4 A	2777.4 A	3942.8 A	3277.4 A	3527.4 A	3452.4 A	3400.8
SD_2= 1st June	1893.2 B	1948.2 B	1938.6 B	1802.6 B	2093.2 B	1930.2 B	1934.33
HSD 5%	323.19	301.27	1779.6	119.01	309.27	176.97	-
Significance	**	**	*	**	**	**	-
(B) Cultivar							
V_1 = FH-114	2416.1 B	2118.6 B	2675.4 B	2307.0 C	2566.1 B	2447.1 B	2421.71
V_2 = FH-142	2928.1 A	2630.6 A	3246.0 A	2781.1 A	2786.6 B	2667.6 B	2937.16
V_3 = MNH-886	2636.6 B	2339.1 B	2900.7 B	2531.9 B	3078.1 A	2959.1 A	2643.75
HSD 5%	243.88	241.88	294.07	215.69	240.18	233.67	-
Significance	**	**	**	**	**	**	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	2358.3 B	2060.8 B	2694.3 B	2310.6 B	2508.3 B	2389.3 B	2386.93
N_2= 200 kg ha^{-1}	2823.1 A	2525.6 A	3144.7 A	2698.4 A	2973.1 A	2854.1 A	2836.50
N_3= 250 kg ha^{-1}	2799.4 A	2501.9 A	3127.5 A	2611.1 A	2949.4 A	2830.4 A	2803.28
HSD 5%	234.21	229.16	262.12	255.6	248.46	242.64	-
Significance	**	**	**	**	**	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	2660.3	2362.8	2988.9	2540	2810.3	2691.3	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.4.5. Ginning Outturn (%)

Cotton harvested from plant is called seed cotton because the fibers are still attached to seed. Ginning is a process by which fibers are removed from the seeds and cleans the fiber. Ginning outturn is the ratio of lint to seed cotton yield. Estimation of cotton yield by computing number of bolls on plant, average boll weight and other yield parameters might be misleading if ginning losses were not considered as it also effects how these parameters relate with the final economic yield (Xian *et al*., 2014). Data regarding ginning outturn for different sowing dates, cultivars and nitrogen levels along-with its interaction at three locations (Faisalabad, Sahiwal and Multan) for two years (2014 and 2015) are presented in Table 4.20. Interactive effects between sowing dates vs cultivars, sowing dates vs nitrogen rates, cultivars vs nitrogen rates and among sowing dates, cultivars and nitrogen rates remained non-significant ($P>0.05$). Year effect was also non-significant.

Sowing dates significantly affected ginning outturn (GOT). Early sowing enhanced GOT compared to late sowing crop. Maximum GOT (42.03%) was recorded in May sown crop, whereas minimum GOT (4.15%) was recorded in June sown crop (Table 4.20).

Cultivars also significantly affected lint to seed cotton ratio. Highest GOT was recorded from cultivar FH-142 at Faisalabad and Sahiwal, whereas cultivar MNH-886 gave highest GOT at Multan. On an average of all locations, cultivar FH-142 performed best and highest GOT was observed (42.9%). Comparatively, less GOT (39.1%) was produced by cultivar FH-114 at all locations.

Nitrogen rates significantly affected GOT at all locations expect 1st year experiment at Faisalabad and both years at Sahiwal. Maximum GOT was observed where 250 kg N ha^{-1} was applied while minimum GOT was attained where 150 kg ha^{-1} was applied.

Table 4.20: Ginning outturn (%) as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	42.76	42.71 A	43.03	40.15 A	42.01 A	41.53 A	42.03
SD_2= 1st June	41.45	40.42 B	41.54	38.87 B	39.59 B	39.07 B	40.15
HSD 5%	-	1.80	-	0.03	1.76	1.70	-
Significance	NS	*	NS	**	*	*	-
(B) Cultivar							
V_1 = FH-114	39.71 B	39.80 B	39.89 B	37.21 B	39.14 B	38.57 B	39.05
V_2 = FH-142	43.92 A	43.45 A	44.10 A	41.24 A	42.49 A	42.02 A	42.87
V_3 = MNH-886	42.67 A	41.46 AB	42.85 A	40.08 A	40.77 AB	40.31 AB	41.35
HSD 5%	1.54	2.63	1.54	1.38	2.62	2.64	-
Significance	**	*	**	**	*	*	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	42.69	40.42 B	41.76	39.81	39.55 B	39.02 B	40.73
N_2= 200 kg ha^{-1}	42.03	41.97 AB	42.21	39.22	41.21 A	40.74 A	41.15
N_3= 250 kg ha^{-1}	41.58	42.32 A	42.87	39.50	41.63 A	41.13 A	41.40
HSD 5%	-	1.69	-	-	1.63	1.64	-
Significance	NS	*	NS	NS	**	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	42.10	41.57	42.28	39.51	40.80	40.30	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.4.6. Harvest Index (%)

Harvest index is the seed cotton yield as a percentage of total above ground biomass and it is the ratio of economic over biological yield. It is a good indicator for identification of yield gap between actual and potential yield. Data regarding harvest index for different sowing dates, cultivars and nitrogen levels along-with its interaction at three locations (Faisalabad, Sahiwal and Multan) for two years (2014 and 2015) are presented in Table 4.21. Interactive effects between sowing dates vs cultivars, sowing dates vs nitrogen rates, cultivars vs nitrogen rates and among sowing dates, cultivars and nitrogen rates remained non-significant ($P>0.05$). Year analysis showed a non-significant relationship between first and second year.

Sowing dates significantly affected harvest index. Experimental results revealed that there was 20% more harvest index in May sown crop as compared to June sown crop. On an average of all locations, May sown crop earned 28.9% harvest index and June sown crop earned 23.1% harvest index.

Cultivars non-significantly affected harvest index of cotton at all locations during both growing seasons. Nitrogen rate significantly affected crop harvest index (Table 4.21). Optimum dose of nitrogen enhanced harvest index. Experimental data depicted that nitrogen rate of 150 kg ha^{-1} increased harvest index (26.9%) which was at par with 200 kg ha^{-1} and lower harvest index (24.1%) was observed where nitrogen rate of 250 kg ha^{-1} was applied. Higher rate of nitrogen significantly enhanced vegetative growth and reduced reproductive growth that ultimately reduced harvest index.

Table 4.21: Harvest Index (%) as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	27.55 A	23.68	32.61	28.86 A	30.05 A	30.55 A	28.88
SD_2= 1st June	22.21 B	22.32	24.10	21.87 B	25.06 B	22.87 B	23.07
HSD 5%	4.58	-	-	1.47	2.92	2.61	-
Significance	*	NS	NS	**	*	**	-
(B) Cultivar							
V_1 = FH-114	24.66	22.49	27.72	24.82	26.37 B	25.78	25.31
V_2 = FH-142	25.72	24.01	29.62	26.45	29.82 A	28.66	27.38
V_3 = MNH-886	24.27	22.50	27.71	24.82	26.48 B	25.69	25.24
HSD 5%	-	-	-	-	3.02	-	-
Significance	NS	NS	NS	NS	*	NS	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	25.43	23.73	29.20	27.16 A	28.53 A	27.59 A	26.94
N_2= 200 kg ha^{-1}	25.49	23.50	28.89	26.19 A	29.20 A	28.33 A	26.93
N_3= 250 kg ha^{-1}	23.72	21.77	26.97	22.73 B	24.93 B	24.21 B	24.06
HSD 5%	-	-	-	2.46	2.49	2.86	-
Significance	NS	NS	NS	**	**	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	24.88	23.00	28.35	25.36	27.56	26.71	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.7. QUALITY PARAMETERS

4.7.1. Fiber fineness (micronaire)

Micronaire or fiber fineness is an important parameter of fiber quality and it refers to the air penetrability of compressed fibers of cotton. This parameter is normally utilized as an indicator of fineness and maturity of fibers. It indirectly specifies the fiber gravimetric fineness which is described as mass per unit fiber length. Some standards are being defined at international level to check these values. Micronaire values ranging between 2 and 8; < 3.0 very fine, 3.0-3.9 fine, 4.0-4.9 average, 5.0-5.9 coarse, > 6.0 very coarse (McAlister and Rogers, 2005).

Sowing date significantly affected micronaire value of cotton fiber. Its value for May sown crop was higher than late sown crop (Table 4.22). Very high or very low value of micronaire indicated lower fiber fineness and medium value of micronaire revealed a good fiber fineness. Experimental results depicted that May sown crop gave good fiber fineness in comparison with June sown cotton. On an average of all locations, micronaire value for May sown crop was higher (4.56) that showed a good fiber fineness and micronaire value for June sown crop was lower that indicated lower (3.52) fiber fineness. Aziz *et al*. (2011) and Deho *et al*. (2012) supported the experimental results and reported higher micronaire values for May sown crop.

Different genotypes showed a significant effect on micronaire value. Higher micronaire value was observed in cultivar FH-142 followed by cultivar MNH-886 while lower fiber fineness was recorded in cultivar FH-114. On an averaged from all locations, cultivar FH-142 produced higher fiber fineness (4.18) in comparison with FH-114 where less fiber fineness (3.96) was observed.

Nitrogen effect on micronaire value was highly significant. Higher dose of nitrogen gave fine quality fiber and lower dose of nitrogen gave less value of fiber fineness. Experimental data depicted that nitrogen rate of 250 kg ha^{-1} gave higher micronaire (4.33) as compared to nitrogen rate of 150 kg ha^{-1} which produced lower micronaire (3.80) and poor quality fiber. Interaction among sowing dates, cultivars and nitrogen rates was non-significant. Year analysis showed a non-significant trend of data.

Table 4.22: Fiber fineness as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	4.30 A	4.66 A	4.81 A	4.67 A	4.45 A	4.85 A	4.62
SD_2= 1st June	3.73 B	3.31 B	3.35 B	3.40 B	3.88 B	3.58 B	3.54
HSD 5%	0.36	0.42	1.01	1.03	0.38	0.41	-
Significance	*	**	*	*	*	**	-
(B) Cultivar							
V_1 = FH-114	3.90 B	3.85 B	3.98 B	3.90 B	4.09 B	4.10 B	3.97
V_2 = FH-142	4.11 A	4.06 A	4.20 A	4.11 A	4.31 A	4.31 A	4.18
V_3 = MNH-886	4.03 AB	4.05 A	4.06 AB	4.08 AB	4.10 B	4.24 AB	4.09
HSD 5%	0.18	0.18	0.20	0.19	0.20	0.19	-
Significance	*	*	*	*	*	*	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	3.75 B	3.71 B	3.81 B	3.73 B	3.92 B	3.94 C	3.78
N_2= 200 kg ha^{-1}	4.36 A	4.33 A	4.41 A	4.37 A	4.46 A	4.54 A	4.41
N_3= 250 kg ha^{-1}	3.93 B	3.92 B	4.02 B	4.00 B	4.12 B	4.17 B	4.03
HSD 5%	0.25	0.26	0.22	0.29	0.21	0.22	-
Significance	**	**	**	**	**	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	4.01	3.99	4.05	4.03	4.17	4.22	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.7.2. Fiber length (mm)

Fiber Length is also known as staple length and it is the mean value of the longest 50% of the fibers. Fiber length was measured in 100th's and in 32's of an inch. Fiber length was statistically non-significant for sowing dates and early sown crop gave higher fiber length than late sown crop during both the growing seasons at all locations (Table 4.23). Very early and very late sowing of cotton adversely affect fiber length as reported by scientists (Ahmad and Razi, 2011) due to very early crop picking resulted in small/immature fiber length. Late cotton picking caused fiber under severe environmental conditions that may convert fiber to more yellow and gray in color as reported by Duckett *et al*. (1999). Higher fiber length (24.2 mm) was observed in May sown crop and lower length of fiber (24.1 mm) was recorded in June sown crop. Duckett *et al*. (1999) also reported analogous results.

Fiber length is also a genetic characteristic and it varies among cultivars. However, it depends on environmental conditions as well. Fiber length for different cultivars was statistically non-significant.

N levels endorsed significant differences of fiber length. Fiber length increased with increasing nitrogen level. Experimental results depicted that longer fiber length (25.83 mm) was contributed by 250 kg ha^{-1} nitrogen followed by optimum dose and shorter fiber length was added by 150 kg ha^{-1} nitrogen.

Interactions among sowing dates, cultivars and nitrogen rates were non-significant. Year analysis showed a non-significant trend of data.

Table 4.23: Fiber length (mm) as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	24.88	23.68	26.41	24.11	23.38	23.08	24.26
SD_2= 1st June	24.68	23.38	24.71	22.61	24.58	24.28	24.04
HSD 5%	-	-	-	-	-	-	-
Significance	NS	NS	NS	NS	NS	NS	-
(B) Cultivar							
V_1 = FH-114	25.00	23.750	25.78	23.58	24.20	23.90	24.36
V_2 = FH-142	24.75	23.506	25.53	23.33	23.95	23.65	24.12
V_3 = MNH-886	24.60	23.35	25.38	23.18	23.80	23.50	23.96
HSD 5%	-	-	-	-	-	-	-
Significance	NS	NS	NS	NS	NS	NS	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	22.63 B	21.38 B	23.41 B	21.21 B	21.83 B	21.53 B	22.00
N_2= 200 kg ha^{-1}	25.25 A	24.00 A	26.03 A	23.83 A	24.45 A	24.15 A	24.62
N_3= 250 kg ha^{-1}	26.46 A	25.21 A	27.25 A	25.05 A	25.66 A	25.36 A	25.83
HSD 5%	1.22	1.22	1.22	1.22	1.22	1.22	-
Significance	**	**	**	**	**	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	24.78	23.53	25.56	23.36	23.98	23.68	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.7.3. Fiber strength (g/tex)

Fiber strength is defined as the force in terms of grams that can break fiber bundle of 1 tex in size whereas tex is basically mass in grams of 1000 meters of fiber length. USDA's cotton classification (2005) categorized fiber strength into following groups; 23 and below (weak), 24 – 25 (intermediate), 26-28 (average), 29-30 (strong) and 31 & above (very strong). Fiber strength was significantly affected by sowing dates, cultivars and sowing dates (Table 4.24). Fiber strength was more in May sown than June sown crop. Experimental data depicted that May sown crop gave higher fiber strength (29.99 g/tex) and crop sown late in the month of June gave lower fiber strength (28.58 g/tex). Experimental results are parallel with the findings of Arshad *et al*. (2001) and Baloch *et al*. (2001) who reported that late planting reduced fiber strength. Moreover, late sown cotton may reach maturity late in season and practically farmers harvest immature cotton that contributes to lower fiber strength, and nep formation, and poor dye uptake (Bradow and Bauer, 1997).

A non-significant result of fiber strength was observed from all cultivars at all locations. Different levels of nitrogen endorsed a significant difference of fiber strength (Table 4.24). Higher dose of nitrogen resulted in higher fiber strength as compared to lower level of nitrogen fertilizer. Experimental results depicted that more fiber strength (29.86 g/tex) was recorded from 250 kg ha^{-1} nitrogen followed by optimum dose and shorter fiber strength (28.53 g/tex) was added by 150 kg ha^{-1} nitrogen. Results are parallel with the findings of Ge (2007). According to him, fiber strength is the major fiber quality parameter influenced by varying rates of nitrogen.

Interaction among sowing dates, cultivars and nitrogen rates was non-significant. Year analysis showed a non-significant trend of data.

Table 4.24: Fiber strength (g/tex) as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	28.89 A	27.89 A	31.57 A	31.17 A	29.39 A	31.02 A	29.99
SD_2= 1st June	28.56 B	27.25 B	28.45 B	28.05 B	28.65 B	30.29 B	28.58
HSD 5%	0.15	0.14	2.57	2.57	0.38	0.38	-
Significance	*	**	*	*	*	*	-
(B) Cultivar							
V_1 = FH-114	28.91	27.76	30.23	29.83	29.21	30.84	29.48
V_2 = FH-142	28.46	27.31	29.68	29.28	28.76	30.73	29.05
V_3 = MNH-886	28.80	27.65	30.12	29.72	29.10	30.40	29.31
HSD 5%	-	-	-	-	-	-	-
Significance	NS	NS	NS	NS	NS	NS	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	28.00 B	26.85 B	29.21 B	28.81 B	28.30 B	29.93 B	28.53
N_2= 200 kg ha^{-1}	28.94 A	27.79 A	30.10 A	29.70 A	29.24 A	30.87 A	29.46
N_3= 250 kg ha^{-1}	29.23A	28.08 A	30.72 A	30.32 A	29.53 A	31.16 A	29.86
HSD 5%	0.85	0.84	0.74	0.74	0.84	0.84	-
Significance	**	**	**	**	**	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	28.72	27.57	30.01	29.61	29.02	30.65	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.8. RADIATION UTILIZATION EFFICIENCIES (RUEs)

4.8.1. Radiation use efficiency for TDM (g MJ^{-1})

Radiation use efficiency or radiation dependent growth is described as unstressed light utilized for biomass conversion. Simply, it is above ground biomass produced by crop plant per unit of light intercepted by crop canopy. Leaf nitrogen content and light intensity affect leaf photosynthesis (Milroy and Bange, 2003). May sowing boosted radiation use efficiency of crop to accumulate dry matter at all locations (Table 4.25). More biomass was accumulated in grams with less utilization of light. The reason behind enhanced RUE_{TDM} was earlier canopy development of crop sown in May as compared to June sown crop that ultimately enhanced more light interception and more accumulation of total dry matter. Additionally, May sown crop experienced insignificant temperature during early days of crop growth that depressed plant respiration and enhanced photosynthesis rate resulted in 15% more RUE_{TDM} (1.33 g MJ^{-1} vs 1.13 g MJ^{-1}) over June sown crop that experienced less photosynthesis rate and enhanced respiration process resulting in less dry matter accumulation and ultimately less RUE_{TDM}. Table 4.19 showed the effect of treatments on radiation use efficiency for total dry matter (RUE_{TDM}) at all locations.

Different genotypes had different efficiencies of radiation interception for dry matter production and a significant difference was observed among cultivars due to specific genetic make-up and canopy structure of all cultivars to survive under severe climatic conditions, so varied in light interception, photosynthetic efficiency and ultimately different RUE_{TDM}. Higher radiation use efficiency was recorded by FH-142 at Faisalabad and Sahiwal. At Multan, radiation utilization efficiency of MNH-886 was higher during both growing seasons. On an average of all locations, FH-142 performed better and maximum RUE_{TDM} (1.26 g MJ^{-1}) was computed from cultivar FH-142 followed by MNH-886 (1.25 g MJ^{-1}) and minimum RUE (1.17 g MJ^{-1}) was computed from FH-114.

RUE_{TDM} was significantly affected by N level at all experimental sites. Nitrogen being important part of crop plant cell, its proteins and different enzymes. Nitrogen play role in photosynthesis process and enhance chlorophyll efficiency to accumulate more dry matter during growing season. On an average of all locations, highest dose of nitrogen increased RUE_{TDM} by 16.8% (1.31g MJ^{-1}) compared to the lower dose of nitrogen where less RUE (1.19

g MJ^{-1}) was computed. The present study corroborated the findings of other researchers (Milroy and Bange, 2003; Arshad, 2006) and they reported similar trend of RUE_{TDM}.

Interaction among sowing dates, cultivars and nitrogen rates was found non-significant. Year analysis showed a non-significant trend of data.

4.8.2. Radiation use efficiency for seed cotton yield (g MJ^{-1})

Sowing dates significantly affected radiation use efficiency for seed cotton yield at all locations. Experimental data revealed that early sown crop was more efficient in utilization of resources as compared to late sown crop (Table 4.26). Comparatively, Radiation use efficiency of May sown crop was higher (0.37 g MJ^{-1}) to convert resources into final yield than June sown crop having less radiation utilization efficiency (0.26 g MJ^{-1}).

Different genotypes have different efficiencies of radiation interception for seed cotton yield and a significant difference was observed among cultivars due to specific genetic make-up and canopy structure of all cultivars to survive under severe climatic conditions, so varied in light interception, photosynthetic efficiency and ultimately different RUE_{YIELD}. Higher radiation use efficiency was recorded by FH-142 at Faisalabad and Sahiwal and radiation utilization efficiency by MNH-886 was higher at Multan during both growing seasons. On an average of all locations, FH-142 performed well and maximum RUE_{YIELD} (0.34 g MJ^{-1}) was computed for FH-142 followed by MNH-886 and minimum RUE (0.28 g MJ^{-1}) was computed from FH-114.

On an average of all locations, highest dose of nitrogen increased RUE_{YIELD} by 16.8% (1.31 g MJ^{-1}) compared to the lower dose of nitrogen where less RUE (1.19 g MJ^{-1}) was computed. Results are at par with

Interaction among sowing dates, cultivars and nitrogen rates was found non-significant. Year analysis showed a non-significant trend of data.

Table 4.25: RUE_{TDM} ($g\ MJ^{-1}$) as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	1.23 A	1.27 A	1.30 A	1.21 A	1.37 A	1.57 A	1.33
SD_2= 1st June	1.06 B	1.17 B	1.03 B	1.02 B	1.13 B	1.37 B	1.13
HSD 5%	0.11	0.08	0.18	0.18	0.24	0.19	-
Significance	*	*	*	*	*	*	-
(B) Cultivar							
V_1 = FH-114	1.07 B	1.18 B	1.10 B	1.07 B	1.20 B	1.40 B	1.17
V_2 = FH-142	1.22 A	1.26 A	1.24 A	1.17 A	1.24 AB	1.45 AB	1.26
V_3 = MNH-886	1.16 AB	1.22 AB	1.16 AB	1.10 AB	1.31 A	1.55 A	1.25
HSD 5%	0.14	0.07	0.13	0.08	0.10	0.14	-
Significance	*	*	*	*	*	*	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	1.10 B	1.15 B	1.12 B	1.19 A	1.13 C	1.38 B	1.19
N_2= 200 kg ha^{-1}	1.15 AB	1.24 A	1.15 B	1.11 B	1.23 B	1.46 B	1.22
N_3= 250 kg ha^{-1}	1.20 A	1.27 A	1.22 A	1.19 A	1.38 A	1.57 A	1.31
HSD 5%	0.08	0.07	0.06	0.07	0.07	0.09	-
Significance	*	**	**	**	**	**	-
Interaction							
A × B	NS	NS	NS	*	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	1.15	1.22	1.16	1.12	1.25	1.47	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

Table 4.26: RUE_{YIELD} (g MJ^{-1}) as affected by site, sowing date and nitrogen rate for different cotton cultivars.

Treatment	Faisalabad		Sahiwal		Multan		Mean
	2014	2015	2014	2015	2014	2015	
(A) Sowing Date							
SD_1= 1st May	0.33 A	0.28 A	0.43 A	0.27 A	0.40 A	0.48 A	0.37
SD_2= 1st June	0.26 B	0.25 B	0.20 B	0.22 B	0.30 B	0.35 B	0.26
HSD 5%	0.04	0.03	0.22	0.02	0.03	0.01	-
Significance	*	*	*	*	**	**	-
(B) Cultivar							
V_1 = FH-114	0.28 B	0.25 B	0.26 B	0.19 B	0.32 B	0.39 B	0.28
V_2 = FH-142	0.31 A	0.29 A	0.36 A	0.28 A	0.34 B	0.45 A	0.34
V_3 = MNH-886	0.29 AB	0.26 AB	0.33 A	0.26 A	0.37 A	0.40 B	0.32
HSD 5%	0.03	0.03	0.04	0.02	0.03	0.03	-
Significance	*	*	**	**	**	**	-
(C) Nitrogen Rate							
N_1= 150 kg ha^{-1}	0.29 B	0.24 B	0.29 C	0.22 B	0.33 B	0.38 B	0.29
N_2= 200 kg ha^{-1}	0.31 A	0.28 A	0.31 B	0.27 A	0.36 A	0.42 AB	0.33
N_3= 250 kg ha^{-1}	0.29 B	0.28 A	0.34 A	0.24 AB	0.35 AB	0.44 A	0.32
HSD 5%	0.02	0.02	0.01	0.02	0.03	0.03	-
Significance	*	**	**	**	*	**	-
Interaction							
A × B	NS	NS	NS	NS	NS	NS	-
A × C	NS	NS	NS	NS	NS	NS	-
B × C	NS	NS	NS	NS	NS	NS	-
A × B × C	NS	NS	NS	NS	NS	NS	-
Year Mean	0.30	0.27	0.31	0.25	0.35	0.41	-
Significance	NS		NS		NS		-

Mean sharing different letters differ significantly at $p \leq 0.05$
*, ** = Significant at 0.05 and 0.01, respectively
NS = Non-Significant

4.9. Crop Growth Modeling

4.9.1 Calculation of genetic coefficients for cultivar

DSSAT model has a set of 15 crop coefficients for simulation of crop phenology, growth and seed cotton yield. These coefficients were determined for each cultivar by repeated interactions to find a best calibration of observed and simulated values. Genetic coefficients are divided into two groups, some contributed more to crop growth while other contributed more to crop yield. In CSM-CROPGRO-Cotton model CSDL, PPSEN, EM-FL, FL-SH, FL-SD, SD-PM, FL-LF, LFMAX, SLAVR and SIZLF controlled cotton growth and slightly contributed to crop yield as well. Whereas, XRFT, WTPSD, SFDUR, SDPDV and PODUR contributed to seed cotton yield and slightly contributed to crop growth.

CSDL was the limited value for short day length below that critical value crop reproductive development proceeds without any effect of day length. CSDL was same for all three cultivars having a value of 23. PPSEN was described as over time comparable response of crop development to photoperiod and 0.01 was the value for all cultivars. EM-FL was the photothermal days between crop emergence to appearance of flowers on crop plant. Its values for cultivar FH-114, FH-142 and MNH-886 were 51,49 and 52 respectively. FL-SH was labelled as Photothermal days between appearance of first flower to appearance of first pod and its values were 22, 16 and 23 for FH-114, FH-142 and MNH-886, respectively. Values for FL-SD were 24, 20 and 30 for FH-114, FH-142 and MNH-886, respectively, which was Photothermal days between appearance of first flower to first seed. Sixth coefficient for cotton growth was SD-PM that was defined as photothermal days between first seed and crop physiological maturity. Its value was higher (55) for FH-114 followed by FH-142 (52) and lower (48) for MNH-886. FL-LF was the time duration between first flower appearance and the end of leaf expansion period and it was 72, 75 and 79 for three cultivars (FH-114, FH-142, MNH-886 respectively). LFMAX was described as high photosynthetic rate of leaf at temperature of 30°C, CO_2 level of 360 ppm and high light intensity (mg $CO_2/m^2/s$) and its values for three cultivars were 1.40, 1.83 and 1.55. Under optimum growth situations, specific leaf area of a cultivar was denoted as SLAVR and calibrated values of cultivars FH-114, FH-142 and MNH-883 were 137, 135 and 127. Peak size of full leaf was defined as SIZLF, whereas its values were 260, 250 and 230 for three cultivars. Eleventh component of crop growth was

XRFT which was defined as maximum daily growth fraction that contributed to its portioning to seed + shell. Cultivar FH-114 was calibrated with value 0.70, cultivar FH-142 was adjusted with value 0.90 and cultivar MNH-886 was calibrated with 0.76 value.

WTPSD was considered as a yield coefficient and it is basically maximum weight per cotton seed in grams. Its value for cultivars FH-114 and FH-142 was same (0.180). MNH-886 was adjusted with a higher value of WTPSD (0.188). Seed filling duration in terms of photothermal days under standard crop growth conditions for pod cohort was SFDUR and it values for three cultivars were 35 (FH-114) and 38 (FH-142 and MNH-886). SDPDV was the average number of seeds in a pod under optimal conditions of crop growth and its values were 25, 30 and 27 for cultivars FH-114, FH-142 and MNH-886 respectively. Last genetic coefficient in CSM-GROPGRO-Cotton model was PODUR that described as time in terms of photothermal days needed to access final pod load for each cultivar under standard crop growth conditions. A less time was assessed for cultivar (8) in comparison with other cultivars where PODUR values were higher (20 and 25).

Table 4.27. Genetic coefficients for three cotton cultivars used in DSSAT

ECO #	VRNAME	CSDL	PPSEN	EM-FL	FL-SH	FL-SD	SD-PM	FL-LF	LFMAX	SLAVR	SIZLF	XRFT	WTPSD	SFDUR	SDPDV	PODUR
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
IB01	FH-114	23	0.01	51	22	24	55	72	1.40	137	260	0.70	0.180	35	25	8
IB02	FH-142	23	0.01	49	16	20	52	75	1.83	135	250	0.90	0.180	38	30	20
IB03	MNH-886	23	0.01	52	23	30	48	79	1.55	127	230	0.76	0.188	38	27	25

Growth coefficients = CSDL, PPSEN, EM-FL, FL-SH, FL-SD, SD-PM, FL-LF, LFMAX, SLAVR and SIZLF

Yield coefficient = XRFT, WTPSD, SFDUR, SDPDV and PODUR

4.9.2 Model calibration and evaluation

Calibration of CROPGRO-Cotton model under DSSAT was done for all cultivars using 2014 experimental data by selecting best treatment of experiment (1st May, 200 kg N ha^{-1}) from all three experimental sites simultaneously and then running crop model. Genetic coefficients were estimated to fetch a closer value of simulated and observed for phenology (anthesis date, maturity date), growth (TDM, LAI) and seed cotton yield by repeated interactions and combination of all 15 genetic coefficients (Table 4.27). Crop model was well adjusted and a good simulation was observed for all three locations based on those coefficients.

Calibrated values of crop phenology, growth and yield were described in Table 4.28. Model performed well and root mean square error (RMSE) was less and within acceptable range that showed a well calibrated result. Further accuracy and performance were evaluated by running crop model remaining treatments at each experimental site during 2014. Model evaluation results for other treatments with same values of crop coefficients were also good and model performed equally well for estimation of anthesis days, maturity days, total dry matter, maximum leaf area index and seed cotton yield. 1:1 graphs were developed for evaluation of simulation values.

Calibration data from all three locations revealed that time in days to anthesis was one day longer by model as compared to observed days to anthesis (Table 4.28). Model calibration results showed that crop reached anthesis stage in 68, 66 and 69 days after sowing for cultivars FH-114, FH-142 and MNH-886, respectively. Comparative value of observed number of days taken by crop for anthesis were 67, 65 and 69. For this parameter, root mean square errors closer to zero (0.57, 0.81, 0.81) were computed. The calibrated data presented in Table 4.28 showed that model simulated same number of days for maturity (149) than the observed ones for FH-142 indicating a perfect calibration of model under set of coefficients while 3-4 days difference for cultivars FH-114 and MNH-886 having RMSE of 6.92, 0 and 4.12 days for cultivars FH-114, FH-142 and MNH-886. CROPGRO-Cotton under DSSAT has been tested by researchers for growth (LAI and TDM), development (anthesis days and Maturity days) and yield simulation of crop sown under different climatic conditions with different crop management practices. Model calibration and validation results were under acceptable range (lower RMSE, higher R^2 and d values) as reported by Jones *et al*. (2003); Ortiz *et al*. (2009);

Pathak *et al*. (2009). The DSSAT model responded differently to both sowing dates and three nitrogen levels as model is very sensitive to time and rate of fertilizer application. Phenological cultivar parameters were the most influential model parameters. The DSSAT model response to various input parameters (soil, climate) and crop management factors were analyzed by various scientists (Ortiz *et al*., 2009; Wajid *et al*., 2014; Corbeels *et al*., 2016) and they demonstrated that in DSSAT sowing date primarily affects the photoperiod hours and nitrogen rate and application timing affects the availability of nitrogen for plants in the soil rootzone. They further reported that the correlations between the input parameters or crop management factors and the output variables were stable over a wide range of seasonal rainfall conditions. The DSSAT model was proved to be an effective tool to make strategic cotton planting choices under changing climates (Arshad *et al*., 2017).

Table 4.28: Comparison between simulated and observed values of different variables for year 2014.

Variables	Obs.	Sim.	R^2	d-stat	RMSE
Cultivar FH-114					
Anthesis days	67	68	0.99	0.84	0.57
Total Dry Matter (kg ha^{-1})	11608	11838	0.99	0.91	273.54
Seed Cotton Yield (kg ha^{-1})	3280	3219	1	0	153.27
Leaf Area Index Maximum	3.97	4.32	0.22	0.29	0.39
Maturity days	156	160	0.40	0.40	6.92
Cultivar FH-142					
Anthesis days	65	66	0.75	0.80	0.81
Total Dry Matter (kg ha^{-1})	12691	12390	0.99	0.92	407.28
Seed Cotton Yield (kg ha^{-1})	4195	3903	0.82	0.84	448.40
Leaf Area Index Maximum	4.42	4.28	0.73	0.75	0.233
Maturity days	149	149	1	1	0
Cultivar MNH-886					
Anthesis days	69	69	0.25	0.63	0.81
Total Dry Matter (kg ha^{-1})	12607	12062	0.99	0.71	581.50
Seed Cotton Yield (kg ha^{-1})	3601	3259	0.70	0.65	401.01
Leaf Area Index Maximum	4.36	4.67	0.23	0.35	0.40
Maturity days	157	160	0.70	0.30	4.12

R_2= coefficient of determination **d-stat=** index of agreement **RMSE=** root mean square error

4.9.3 Model validation

To check the model efficiency and simulation accuracy, model was run with same genetic coefficients for independent set of second year experimental data (2015). First year data for calibration and second year data for validation has been used in many researches (Mubeen *et al*., 2013; Wajid *et al*., 2013). It provides a basis to evaluate model accuracy under various agro-climatic conditions. Simulation results were quite reasonable for all output parameters. RMSE and d-stat values of evaluation and validation were computed. 1:1 graphs were developed to show observed and simulated values (Figure 4.18). Equivalent results of crop simulation are discussed below.

4.9.4. Crop Phenology

(1) Anthesis days

According to overall model simulations, crop sown on 1st May reached anthesis stage in 65-69 days after sowing at Faisalabad, 67-70 days after sowing at Sahiwal and 65-69 days after sowing at Multan. Crop sown on 1st June reached anthesis stage in 63-68 days at Faisalabad, 65-68 days at Sahiwal and 57-61 days after sowing at Multan in all treatments. Equivalent values from observed data for 1st May sown crop ranged between 65-68 days at Faisalabad, 66-69 days at Sahiwal and 56-61 days at Multan and for 1st June sown crop, 61-68 days, 65-67 days and 57-61 days for three locations respectively. Both simulated and observed values verified that model worked well under these different environmental conditions.

Statistical indices also proved good model performance. Root mean square error (RMSE) of 1st May sown crop was ranged between 0.61 to 1 whereas RMSE of 1st June sown crop was between 0.94 to 1 (Table 4.29). Index of agreement (d) of both sowing was greater than 0.80 for all experimental sites (Table 4.30).

Validation results of crop model for all three locations were also good that showed best performance of model. Simulated data from model run with second year experimental values depicted that crop took almost same number of days for anthesis. Model data showed that crop sown on 1st May took 64-70 days at Faisalabad site, 75-79 days at Sahiwal site and 66-72 days after sowing at Multan site whereas 1st May sown crop took 61-67 days, 59-71 days and 58-67 days after sowing for anthesis at Faisalabad, Sahiwal and Multan respectively. Comparable observed values ranged between 54-79 for all locations. Validation results confirmed the usefulness of crop model.

Root mean square error (RMSE) of 1st May and 1st June sown crop was ranged from 1.15 to 1.73 and 1.15 to 1.69 respectively during model validation with second year data. Index of agreement (d) of 1st May and 1st June sown crop was higher than 0.80 for all locations except 1st May sown crop at Sahiwal where calculated d value was 0.74. Figure 4.18 (A, C, E) illustrates the scattering of simulated and observed anthesis days around the regression line. Values were closer to 1:1 line. Li *et al*. (2009) and Wajid *et al*. (2014) confirmed that CROPGRO-Cotton simulates days to flowering close to the observed values with RMSE lower than 3 d which shows good model calibration.

(2) Maturity days

Crop sown on 1st May took more days to complete its growth period as compared to crop sown late on 1st June. According to model simulations, May sown crop matured in 149-158 days (Faisalabad), 150-158 days (Sahiwal) and 156-161 days (Multan) whereas June sown crop matured in 143-151 days at Faisalabad, 147-153 days at Sahiwal and 145-152 days at Multan. The observations for May and June sown crop for maturity were 143-155 days (Faisalabad), 149-159 days (Sahiwal) and 143-160 days (Multan), respectively in year 2014 which indicate quite good working of DSSAT model to simulate maturity date for all three environmental conditions. Higher rate of nitrogen showed 1-2 day delay in maturing crop according to simulation results. On the other hand, all the cultivars except FH-142 showed a difference of one day in simulated and observed and model over simulated in days taken to crop maturity.

Root mean square error ranged between 1.06 to 1.45 and 1.56 to 1.97 for 1st May and 1st June sown crop respectively during this year (Table 4.29). Index of agreement (d) was greater than 0.80 except 1st June sown crop at Faisalabad. It showed that model simulated crop maturity days quite well for Faisalabad and Multan while slightly over simulated for Sahiwal (Table 4.30).

Validation results showed that cotton crop sown on 1st May took 159-162 days (Faisalabad), 161-169 days (Sahiwal) and 158-162 days (Multan) days after sowing for maturity while crop sown of 1st June takes 146-156 days (Faisalabad), 153-167 days (Sahiwal) and 149-155 days (Multan) days after sowing for crop maturity. The observed values ranged from 145-169 days for all locations, somehow closer to simulation results which ensured higher performance of model.

Root mean square error (RMSE) of 1st May and 1st June sown crop was between 1.85 to 2.40 and 1.69 to 2.72 respectively during 2015. Index of agreement (d) of 1st May and 1st June sown crop was greater than 0.80 for Faisalabad and Sahiwal except for Multan where calculated d value was greater than 0.70. Figure 4.18 (B, D, F) illustrates the scattering of simulated and observed maturity days around the regression line. Values were closer to 1:1 line. Model results were similar with the findings of Li *et al*. (2009) and Wajid *et al*. (2014) who reported that RMSE values of days to maturity were less than 2 days.

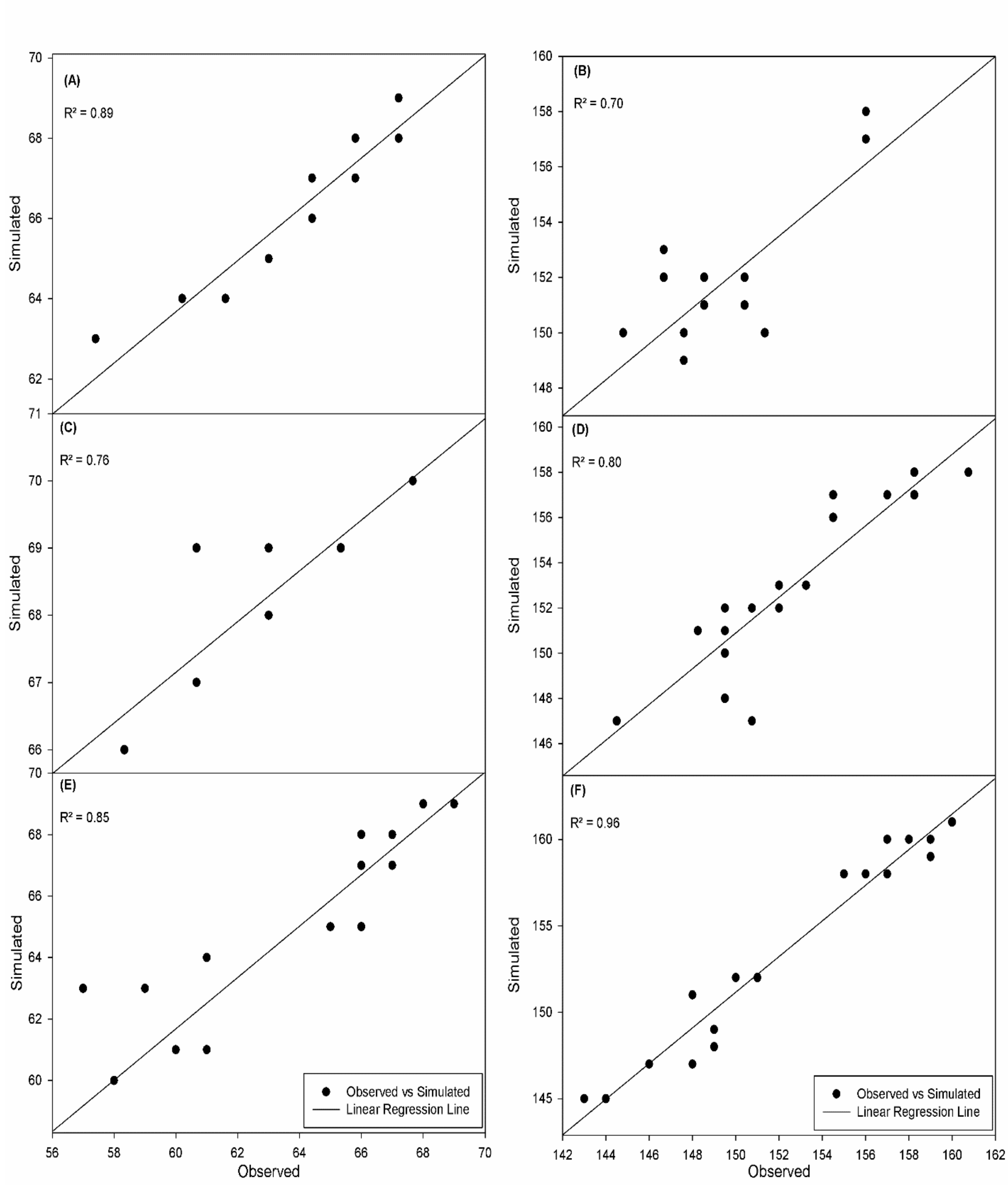

Figure 4.18: Relationship between simulated and observed values of anthesis date and maturity date for cotton cultivars sown at Faisalabad (A, B), Sahiwal (C, D) and Multan (E, F), respectively during growing season of 2014.

4.9.5. Crop Growth

(3) Leaf Area Index (LAI)

Data of the calibrated model show that simulated values were close to observed ones (Table 4.28). Model simulated slightly higher LAI. During 2014, model prediction for earlier sown crop was higher than late sown crop. Calibration data depicts that model slightly overpredicted leaf area index value for Multan while almost same value was predicted for Faisalabad and Sahiwal. Calibrated values of leaf area index were 3.97 (observed) and 4.32 (simulated) having root mean square error of 0.39 for cultivar FH-114; 4.42 (observed) 4.28 (simulated) having RMSE of 0.23 for cultivar FH-142; 4.36 (observed) and 4.67 (simulated) with RMSE of 0.40 which shows a well calibration results of DSSAT model. Model simulation showed that May sown crop with higher nitrogen rate result in higher value of leaf area index crop. While, 1st May sown crop showed higher LAI in simulated and observed results. Figure 4.19 (A, C, E) illustrated calibrated graphs of leaf area index for cultivar FH-114 with 200 kg N ha^{-1} sown on 1st May at Faisalabad, Sahiwal and Multan. Model results were closer to observed seasonal leaf area index and slightly over simulated LAI for cultivar FH-114 at Sahiwal and Multan with RMSE 0.56 and 0.58, respectively. Figure 4.20 (A, C, E) illustrated calibrated graphs of leaf area index for cultivar FH-142 with 200 kg N ha^{-1} sown on 1st May at Faisalabad, Sahiwal and Multan. Model over simulated LAI for cultivar FH-142 with RMSE 0.83. Figure 4.21 (A, C, E) illustrated calibrated graphs of leaf area index for cultivar MNH-886 with 200 kg N ha^{-1} sown on 1st May at Faisalabad, Sahiwal and Multan. A closer values of observed and simulated LAI was obtained for cultivar MNH-886 at all three locations.

Root mean square error of model evaluation results ranged between 0.37 to 0.62 and 0.48 to 0.61 for 1st May and 1st June sown crop respectively (Table 4.29) while index of agreement (d) was greater than 0.70 which showed fitness of model (Table 4.30). Model showed LAI value slightly under simulated for 1st June sown crop.

Model was validated with second year data. Validation results showed that cotton crop sown on 1st May gave higher value of LAI at all locations as compared to crop sown on 1st June and observed values were closer to simulation results which confirmed higher performance of model.

Root mean square error (RMSE) of 1st May and 1st June sown crop was between 0.21

to 0.61 and 0.40 to 0.51 respectively during 2015. Index of agreement (d) of 1st May and 1st June sown crop was greater than 0.75 for all locations except June sown crop at Sahiwal where calculated d value was greater than 0.70. Model results were similar with the findings of Wajid *et al*. (2014) and Ortiz *et al*. (2009) who reported that RMSE values of LAI simulated with DSSAT-CROPGRO were less than 1 and good agreement of d statistic between observed and simulated data.

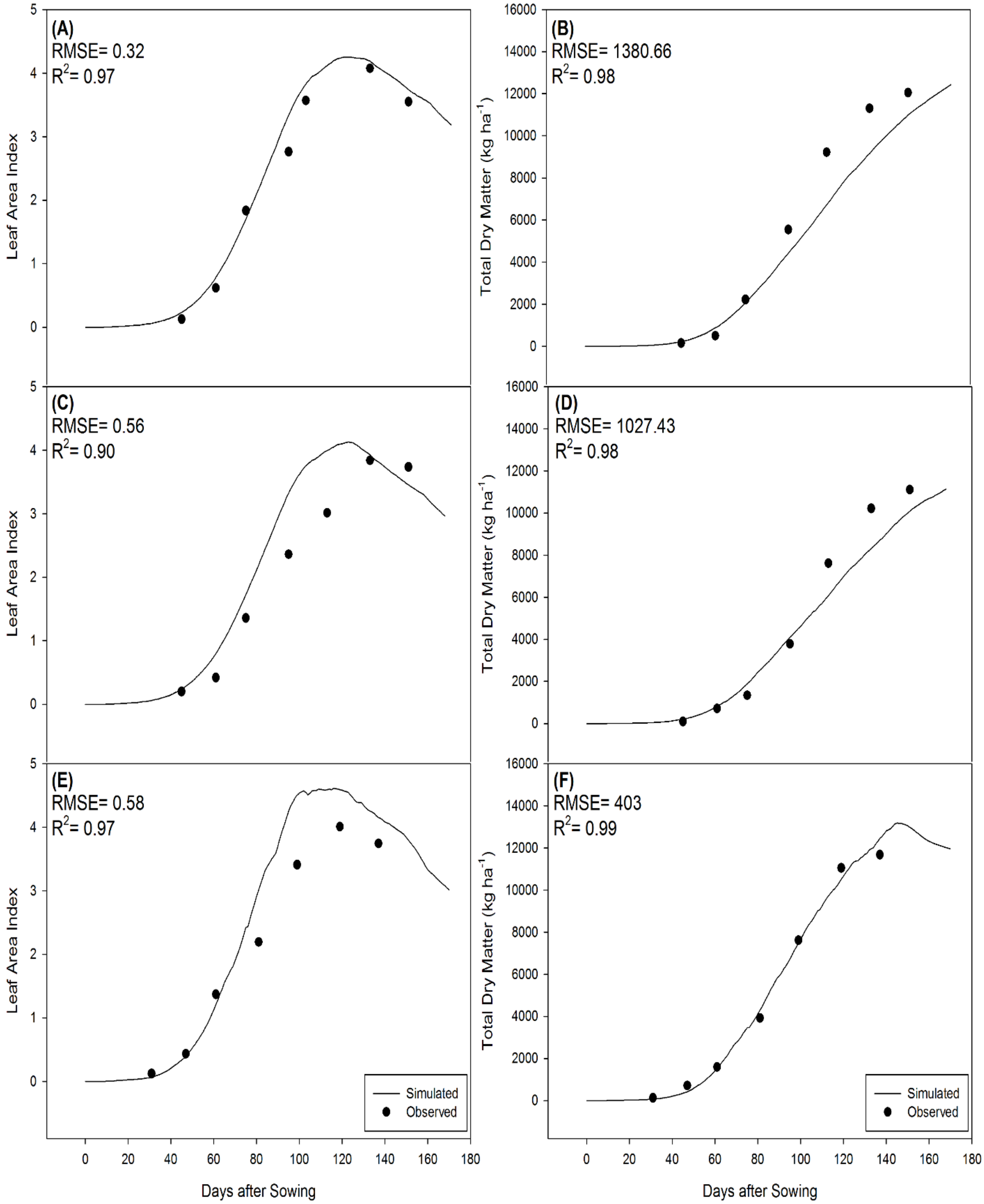

Figure 4.19: Calibrated graphs of leaf area index and total dry matter for cultivar FH-114 with 200 kg N ha^{-1} sown on 1st May at Faisalabad (A, B), Sahiwal (C, D) and Multan (E, F), respectively.

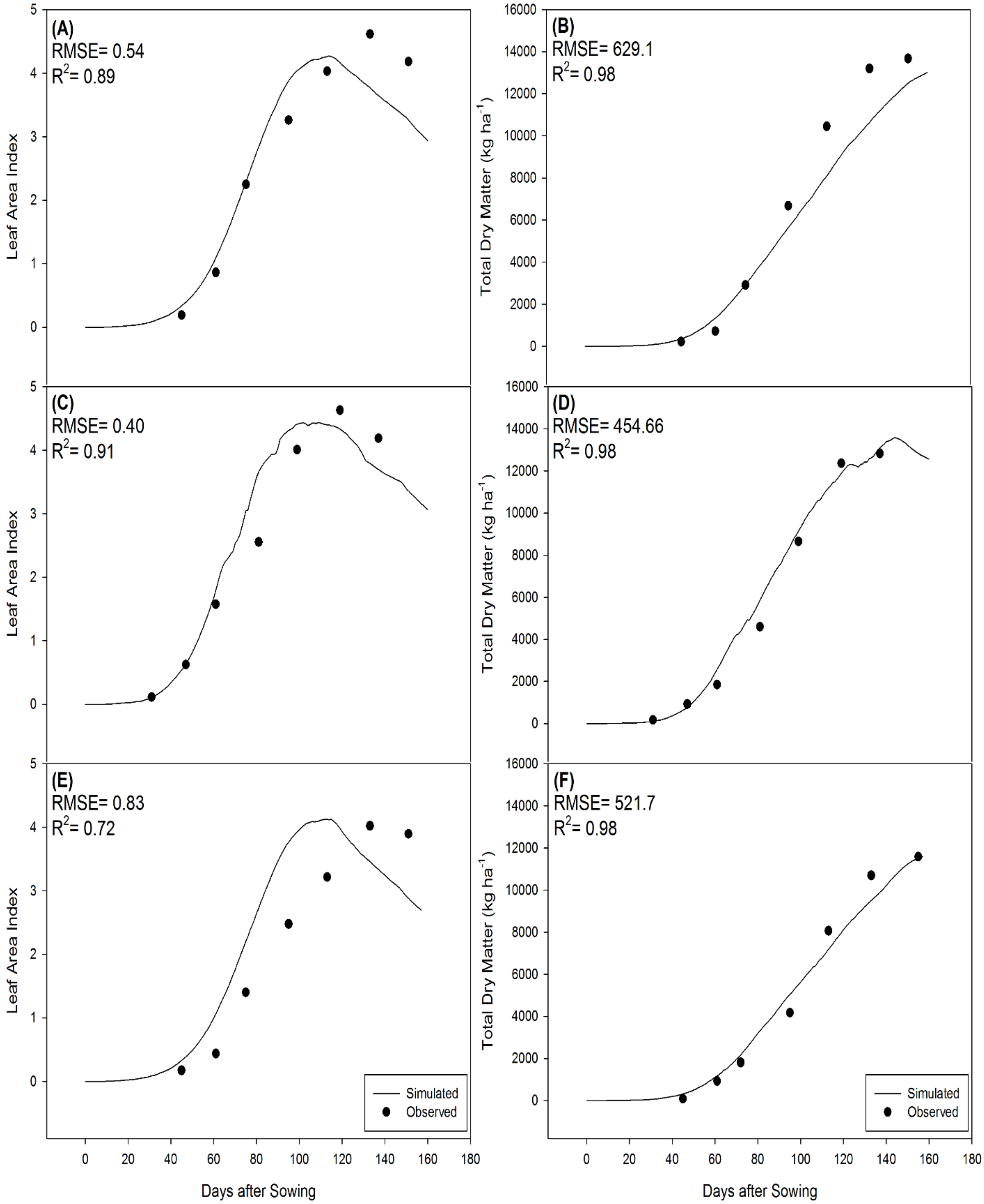

Figure 4.20: Calibration results of leaf area index and total dry matter for cultivar FH-142 with 200 kg N ha^{-1} sown on 1st May at Faisalabad (A, B), Sahiwal (C, D) and Multan (E, F), respectively.

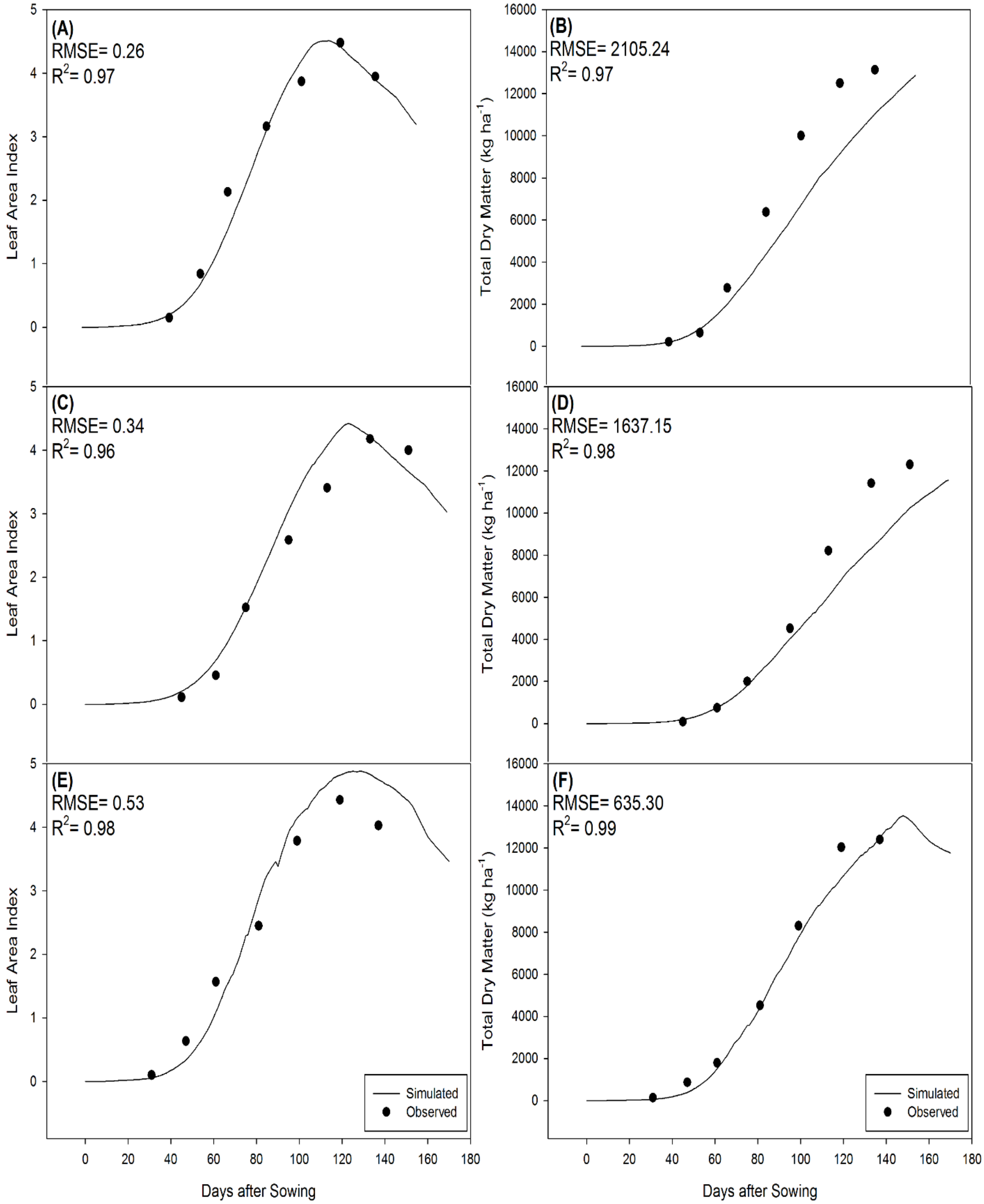

Figure 4.21: Calibrated graphs of leaf area index and total dry matter for cultivar MNH-886 with 200 kg N ha^{-1} sown on 1st May at Faisalabad (A, B), Sahiwal (C, D) and Multan (E, F), respectively.

(4) Total Dry Matter (TDM)

Dry matter accumulation (TDM) simulations by DSSAT were closer to the observed values indicating that cultivar FH-142 have more potential of producing total dry matter. The data in Figures (4.19, 4.20, 4.21) clearly indicating close simulated and observed total dry matter values. Data showed that model slightly under simulated total dry matter for Faisalabad. Overall calibrated values were 11608 kg ha^{-1} (observed) and 11838 kg ha^{-1} (simulated) with RMSE 273.54 kg ha^{-1} for cultivar FH-114; 12691 kg ha^{-1} (observed) and 12390 kg ha^{-1} (simulated) having root mean square error of 407.28 kg ha^{-1} for cultivar FH-142; 12607 kg ha^{-1} (observed) and 12062 kg ha^{-1} (simulated) having RMSE of 581.50 kg ha^{-1} for cultivar MNH-886 which shows a good calibration results of DSSAT model. Higher nitrogen showed higher value of TDM according to simulation results. Crop sown on 1st May showed higher TDM in simulated and observed results. Figure 4.19 (B, D, F) illustrated calibrated graphs of total dry matter for cultivar FH-114 with 200 kg N ha^{-1} sown on 1st May at Faisalabad, Sahiwal and Multan. Model slightly under simulated TDM for cultivar FH-114 at Faisalabad having RMSE of 1380.66 kg ha^{-1}. Figure 4.20 (B, D, F) illustrated calibrated graphs of total dry matter for cultivar FH-142 with 200 kg N ha^{-1} sown on 1st May at Faisalabad, Sahiwal and Multan. Model results were slightly under simulated for cultivar FH-142 with RMSE value of 629.1 kg ha^{-1}. Figure 4.21 (B, D, F) illustrated calibrated graphs of total dry matter for cultivar MNH-886 with 200 kg N ha^{-1} sown on 1st May at Faisalabad, Sahiwal and Multan. Under simulated seasonal TDM was observed for cultivar MNH-886 at Faisalabad and Sahiwal having higher RMSE of 2105.24 and 1637.15 kg ha^{-1} showing poor calibration of cultivar at both locations.

Root mean square error ranged between 278 to 515 and 490 to 534 for 1st May and 1st June sown crop respectively (Table 4.29) while index of agreement (d) was greater than 0.90 for both sowing crop at all locations (Table 4.30).

Model was validated with second year experiment. Validation results showed that cotton crop sown on 1st May gave higher value of TDM at all locations as compared to crop sown on 1st June and observed values were closer to simulation results which shows high efficiency of model.

Root mean square error (RMSE) of 1st May and 1st June sown crop was between 499 to 573 and 512 to 562 respectively during 2015 (Table 4.29) while index of agreement (d) of 1st May and 1st June sown crop was greater than 0.90 for all locations (Table 4.30). Model calibration and validation results were similar with the findings of Wajid *et al*. (2014) and Ortiz *et al*. (2009) reported similar results and concluded that DSSAT-CROPGRO simulate TDM with lower RMSE (367 to 497 kg ha^{-1}).

4.9.6. Seed Cotton Yield

DSSAT model estimated seed cotton yield (SCY) well for all cultivars (Table 4.28). Calibrated data showed that model simulated higher SCY for cultivars sown on 1st May nitrogen dose of 200 kg ha^{-1}. Overall calibrated value was 3280 kg ha^{-1} (observed) and 3219 kg ha^{-1} (simulated) having RMSE of 153.27 kg ha^{-1} for cultivar FH-114; 4195 kg ha^{-1} (observed) and 3903 kg ha^{-1} (simulated) having root mean square error of 448.40 kg ha^{-1}; 3601 kg ha^{-1} (observed) 3259 kg ha^{-1} (simulated) with RMSE of 401.01 kg ha^{-1} which shows a well calibration results of DSSAT model. Optimum nitrogen showed higher value of SCY for 1st May sown crop while higher dose of nitrogen showed higher value of SCY according to simulation results. Model evaluation results were quite well that shows a higher performance of model.

Root mean square error of evaluation results ranged between 197 to 288 and 276 to 419 for 1st May and 1st June sown crop respectively (Table 4.29) while index of agreement (d) was greater than 0.70 for both sowing crop at all locations (Table 4.30).

Model was validated with second year data. Validation results showed that cotton crop sown on 1st May gave higher value of SCY at all locations as compared to crop sown on 1st June and observed values were closer to simulation results which shows good performance of model.

Root mean square error (RMSE) of 1st May and 1st June sown crop was between 301 to 357 and 177 to 422 respectively during 2015 (Table 4.29) while index of agreement (d) of 1st May and 1st June sown crop was less than 0.70 for all locations expect for 1st May sown crop at Faisalabad and Multan having d value greater than 0.80 (Table 4.30). Model calibration and validation results were similar with the findings of Wajid *et al*. (2014) who reported that RMSE values of seed cotton yield were lower (122 to 227 kg ha^{-1}) which showed good model performance.

Table 4.29: Root Mean Square Error (RMSE) of different cotton variables sown at three locations during 2014 and 2015.

Variable	Faisalabad				Sahiwal				Multan			
	2014		2015		2014		2015		2014		2015	
	SD_1	SD_2	SD_1	SD_2	SD_1	SD_2	SD_1	SD_2	SD_1	SD_2	SD_1	SD_2
Anthesis days	0.61	0.94	1.15	1.37	1	0.94	1.73	1.15	1	1	1.42	1.69
Total dry matter (kg ha^{-1})	278	496	573	562	515	534	499	512	467	490	567	516
Cotton Yield (kg ha^{-1})	288	276	301	422	197	412	357	177	237	419	304	376
Leaf area index	0.37	0.53	0.21	0.45	0.62	0.61	0.61	0.51	0.39	0.48	0.32	0.40
Maturity days	1.06	1.97	2.40	1.69	1.45	1.85	1.85	1.82	1.11	1.56	2.02	2.72

Table 4.30: d-statistics value of different cotton variables sown at three locations during 2014 and 2015.

Variable	Faisalabad				Sahiwal				Multan			
	2014		2015		2014		2015		2014		2015	
	SD_1	SD_2	SD_1	SD_2	SD_1	SD_2	SD_1	SD_2	SD_1	SD_2	SD_1	SD_2
Anthesis days	0.93	0.93	0.91	0.83	0.84	0.81	0.74	0.97	0.86	0.92	0.83	0.94
Total dry matter (kg ha^{-1})	0.98	0.93	0.95	0.94	0.94	0.95	0.97	0.93	0.97	0.95	0.94	0.93
Cotton Yield (kg ha^{-1})	0.71	0.78	0.84	0.71	0.84	0.73	0.83	0.79	0.77	0.70	0.80	0.74
Leaf area index	0.72	0.70	0.83	0.77	0.71	0.71	0.78	0.71	0.73	0.77	0.78	0.82
Maturity days	0.96	0.74	0.94	0.93	0.94	0.80	0.88	0.97	0.87	0.90	0.76	0.77

4.10. Cotton productivity under future climate

Climate is a long-term (timescale: 30 year) representation of atmospheric and weather processes at any particular region characterized by distribution of extreme meteorological events. Timescale of 30 years is a climatological normal period (Schott, 2011). According to Intergovernmental panel on climate change (IPCC) 21st century was divided into three centuries, early century from 2010-2039; mid century from 2040-2069; late century 2070-2100.

Future climate data was acquired from Pakistan Meteorological Department, Islamabad. Statistical downscaling of future climatic data was done from course resolution global circulation model (GCM). CMIP5 data was downscaled to fine spatial resolution/scale. Five climate models were run for simulation of future data of temperature, rainfall and carbon dioxide. Details of models are given in Table 4.26.

According to climate model simulations, 1.7°C temperature will rise in early century (2010-2039), 3.7°C will rise in mid century (2040-2069) and 7°C will increase in late century (2070-2100) at Faisalabad and Sahiwal. Whereas 1.9°C, 4.2°C and 7.6°C will rise in early, mid and late century at Multan. Rainfall pattern will also change till end of 21st century and 44%, 37%, 105% rainfall will increase during early century, 55%, 48%, 118% in mid century and 77%, 71%, 165% will increase in late century at Faisalabad, Sahiwal and Multan. Carbon dioxide level will also increase till end of 21st century. It was simulated that CO_2 level will be elevated from current value of 400 ppm to 460 ppm till end of early century, 560 ppm till end of mid century and 660 ppm till end of late century at all locations.

Climate change impact assessment was analyzed using seasonal analysis tool of DSSAT model and climatic scenario was based on climatological relationships that gives clear description of future climate. DSSAT model was run with 30 years (1984-2015) baseline data weather data of maximum temperature, minimum temperature, solar radiation and rainfall representing past and present weather conditions. Based on future rise in temperature, CO_2 and rainfall, climate change impact on cotton crop was assessed. Crop model was run with observed soil data, crop management data of each experimental site and with the help of environmental modification option in crop management file, future climate data value were added to model.

4.10.1. Cotton productivity in early century

Results from seasonal analysis revealed that with elevated CO_2 level, seed cotton yield will be increased while rise in temperature or rainfall will reduce crop yield. Figure 4.22 depicts the climate change impact on cotton crop sown at Faisalabad, Sahiwal and Multan in future.

Model results showed that there will be 16% yield loss under 1.7°C rise in temperature, 460 ppm CO_2 and 44.4% more rainfall at Faisalabad in early century (till 2039). Figure 4.22 depicts the climate change impact on cotton crop sown at Sahiwal in future. Model results showed that there will be 23% yield reduction under 1.7°C rise in temperature, 460 ppm CO_2 and 37.1% more rainfall at Sahiwal in early century (till 2039). Figure 4.22 depicts the climate change impact on cotton crop sown at Multan in future. Model results showed that there will be 20% yield loss under 1.9°C rise in temperature, 460 ppm CO_2 and 105% more rainfall at Multan in early century (till 2039).

4.10.2. Cotton productivity in mid century

Model results showed that there will be 33% yield loss under 7°C rise in temperature, 560 ppm CO_2 and 55.5% more rainfall at Faisalabad in mid century (till 2069). Figure 4.22 depicts the climate change impact on cotton crop sown at Sahiwal in future. Model results showed that there will be 34% yield reduction under 3.7°C rise in temperature, 560 ppm CO_2 and 48.6% more rainfall at Sahiwal in mid century (till 2069). Figure 4.22 depicts the climate change impact on cotton crop sown at Multan in future. Model results showed that there will be 32% yield loss under 4.2°C rise in temperature, 560 ppm CO_2 and 118% more rainfall at Multan in mid century (till 2069).

4.10.3. Cotton productivity in late century

Model results showed that there will be 45% yield loss under 7°C rise in temperature, 660 ppm CO_2 and 77.7% more rainfall at Faisalabad in late century (till 2100). Figure 4.22 depicts the climate change impact on cotton crop sown at Sahiwal in future. Model results showed that there will be 36% yield reduction under 7°C rise in temperature, 660 ppm CO_2 and 71.4% more rainfall at Sahiwal in late century (till 2100). Figure 4.22 depicts the climate change impact on cotton crop sown at Multan in future. Model results showed that there will be 35% yield loss under 7.6°C rise in temperature, 660 ppm CO_2 and 165% more rainfall at Multan in late century (till 2100). There is a lot of difference between climatic conditions of Faisalabad and Sahiwal. Sahiwal is the best area for sowing cotton as far as climate and soil conditions. The TDM and SCYs are always higher at Sahiwal location comparative to Faisalabad, so any anomaly or climatic shock brings drastic change in yields. Model results showed higher yield loss at Faisalabad (16%, 33%, 45%), Sahiwal (23.0%, 34%, 36%) and Multan (20%, 32%, 35%) in early, mid and late century, respectively. Dry semiarid climatic conditions at Faisalabad, wet semiarid climatic conditions at Sahiwal and arid climatic conditions at Multan that may induce heat stress with further rise in temperature and CO_2. This may result in more boll shedding and less yield with greater increase in temperatures. Model results are in line with Kakani *et al*. (2005); Pettigrew (2008) and Singh *et al*. (2007) who confirmed that heat stress and other climatic shocks will reduce crop yield.

4.9. Strategy analysis for cotton crop

Strategy analysis showed that timely sown of cotton cultivar FH-142 in May with 200 kg N ha^{-1} can be viable option to get maximum yield at Faisalabad and Sahiwal and while MNH-886 sown on 1st May at Multan with 200 kg N ha^{-1} can perform best under future changing climate.

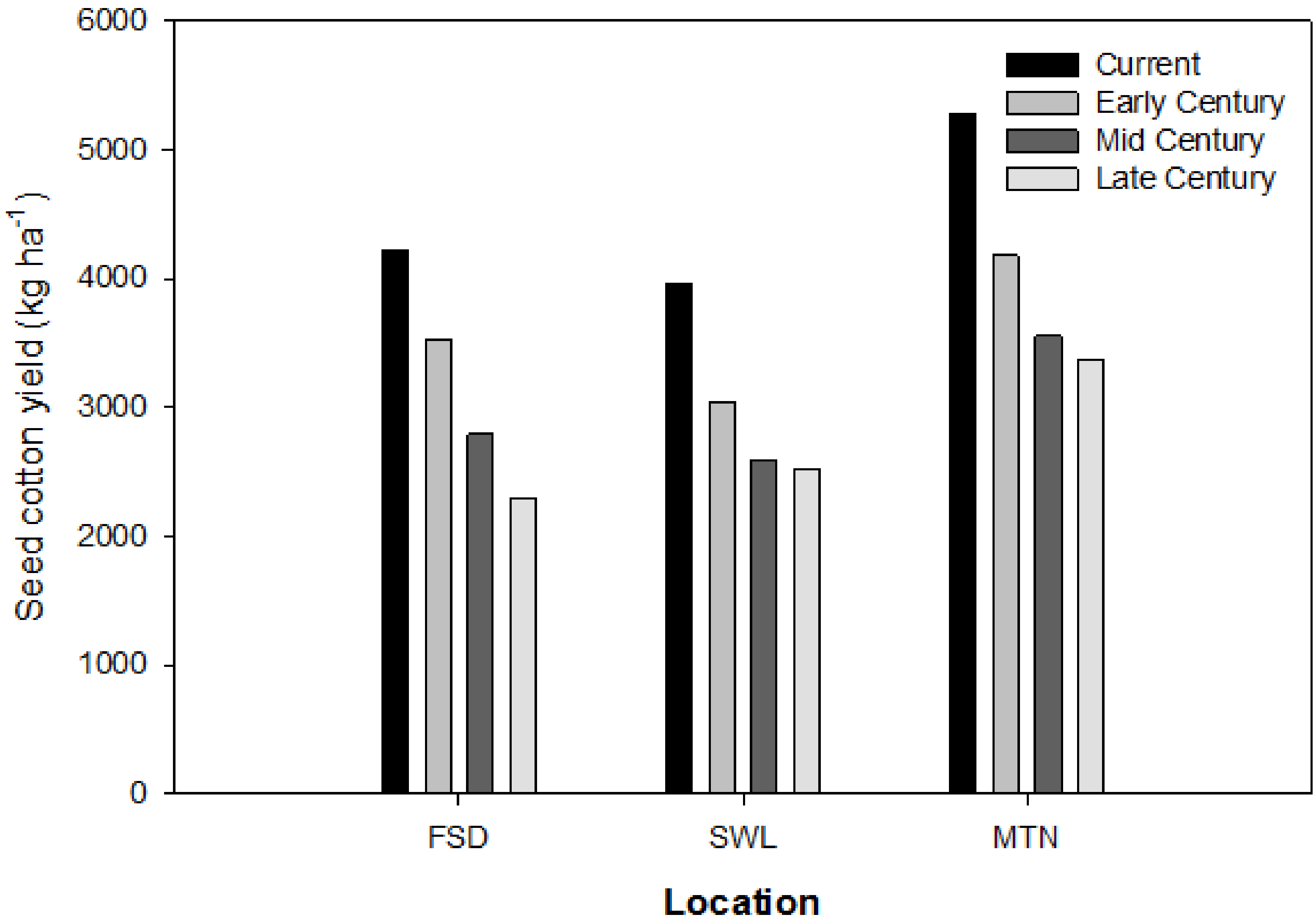

Figure 4.22: Climate Change Impact on Cotton yield at Faisalabad, Sahiwal and Multan during early, mid and late century.

4.11. Geographic Information System (GIS) maps of cotton productivity

Raster package was developed by Hijmans *et al*. (2016) to analyze, manipulate and simulate geospatial data. This package was utilized to perform some basic and advanced functions that also assist in processing of very large data files. Crop model was run with daily weather data of WorldClim (Fick and Hijmans *et al*., 2017) for all districts of Punjab. Potential yield was simulated yield as a function of weather data with the help of Random Forest algorithm (Breiman, 2001). Script was run with R-package "randomForest" and function of this package was classification and regression based on a regression trees using random inputs (Liaw and Wiener, 2002).

4.11.1. GIS maps with Metamodel

Dismo package in R was another package developed by Hijmans *et al*. (2017) as functions for species distribution modeling. This package was designed to forecast geographic distributions of species with their form of occurrences at different environmental sites. Dismo package perform distinct functions that can be helpful in advanced regression processes. Under dismo package, "biovars" was utilized to generate all bioclimatic variables as independent variables from monthly data of climate including maximum temperature, minimum temperature and solar radiation. Scientists use these variables in various species distribution models (Booth *et al*., 2014; Elith and Leathwick, 2009). A model was developed where yield was considered as a function of a set of bioclimatic variables (MBIO). These variables include 18 layers/columns (bio1-bio18) which are:

(1) Mean annual temperature
(2) Mean daytime range (average of maximum temperature - minimum temperature)
(3) Isothermality (bio2/bio7) (* 100)
(4) Temperature seasonality (standard deviation *100)
(5) Maximum temperature of hottest month
(6) Minimum temperature of chilliest month
(7) Annual range of temperature (bio5 - bio6)
(8) Mean temperature of the rainiest quarter
(9) Mean temperature of driest quarter
(10) Mean temperature of hottest quarter

(11) Mean temperature of chilliest quarter

(12) Total (annual) rainfall

(13) Rainfall of rainiest month

(14) Rainfall of driest month

(15) Rainfall seasonality (coefficient of variation)

(16) Rainfall of rainiest quarter

(17) Rainfall of driest quarter

(18) Rainfall of hottest quarter

Figure 4.23 showed cotton productivity map developed with Metamodel. Geospatial analysis showed that under future climate change scenario, cotton yield will be severely affected with rise in temperature, rainfall and CO_2. Meta model predicted that cotton production will be severely affected in whole Punjab region if sown in the month of May and yield will be around 2500 kg ha^{-1} in most of the north, central and south regions of Punjab. To achieve a higher crop yield of more than 4000 kg ha^{-1}, crop should be sown at Dera Ghazi Khan, Okara, Pakpattan, Sahiwal and Bahawalnagar regions of Punjab. However, cotton crop may compete for land use with other currently cultivated crops. Reallocation of crops in such situation would be best to develop a strategic plan for agriculture of Pakistan.

4.11.2. GIS maps with Weather Generator

Daily weather data of various locations was amassed to attain average monthly data of climate. That long-term mean data was further utilized to generate daily weather data. Actual computed climatic data was used for all locations in Punjab that permitted to remove the effect of interpolation and weather simulation as done by another method in Weather Generator. This was a very simplified Weather Generator. Monthly means were allocated to 15^{th} of each month. With the help of linear interpolation technique, values for in-between days were computed. Furthermore, these computed values were considered as input dataset to run crop model. Weather data of CMIP5 with RCP 8.5 was acquired for future run of model.

Geospatial analysis depicted in Figure 4.23 that crop sown in the month of May in future would decrease cotton yield in almost 70% of Punjab. Upper Punjab districts would be somehow good with an average cotton production of 1000 to 2500 kg ha^{-1}. Only some areas of Khushab and Mianwali would be good for production of cotton. Similar to Meta Model predictions, Dera Ghazi Khan could provide home for cotton to get maximum yield of more than 4000 kg ha^{-1}. In comparison of Weather Generator and Meta Model approach performed well to depict the future yield of cotton.

Weather Generator approach was further utilized to generate future of cotton production in context of different sowing dates. Model was run for sowing of cotton in the month of April, May, June and July. Dramatic difference in seed cotton yield was being observed by change in cotton sowing. Geospatial analysis with future climatic data showed that crop sown in the month of April and May at Dera Ghazi Khan, Khushab, Mianwali would be best to attain more than 4000 kg ha^{-1} cotton yield whereas upper and central Punjab would produce lower seed cotton yield ranging between 1000 to 3000 kg ha^{-1} and cotton crop would be under heat stress in southern part of Punjab (Figure 4.24). One month late sowing of crop in the month of June would be best to obtain higher seed cotton (> 4000 kg ha^{-1}) yield in whole upper Punjab and some parts of central Punjab whereas yield would be around 2000 to 3000 kg ha^{-1} in southern Punjab if crop would be sown in the month of June. Further delay in sowing in the month of July would critically effect on seed cotton yield where maximum yield would be less than 2500 kg ha^{-1} in upper Punjab and further low in lower Punjab. Overall results depicted that cotton crop sown in the month of June would be best to obtain maximum yield and rezoning of cotton is important under future changing climate scenarios.

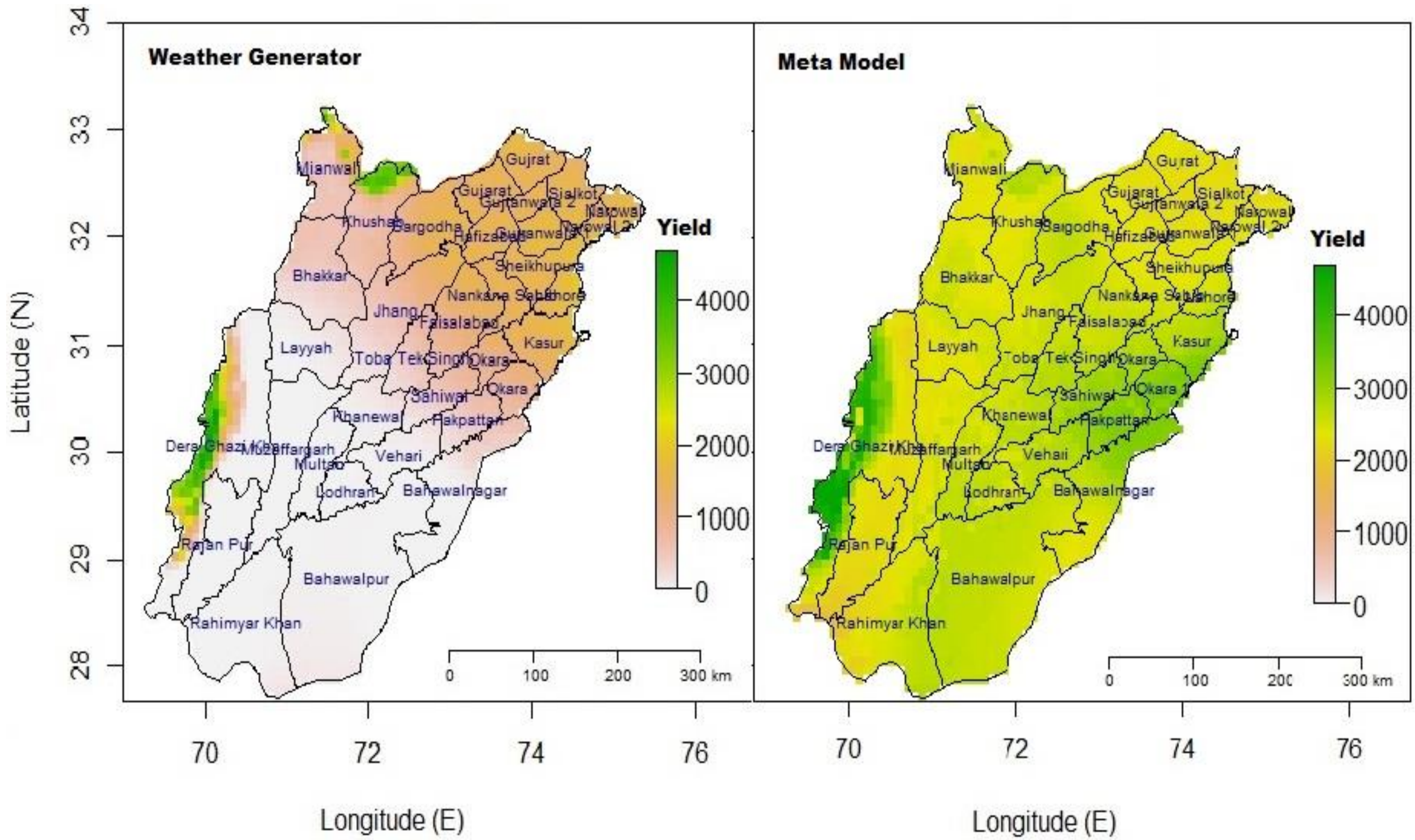

Figure 4.23: Cotton productivity map of Punjab under early century scenario CMIP5 (RCP8.5) developed with Weather Generator and Metamodel approach.

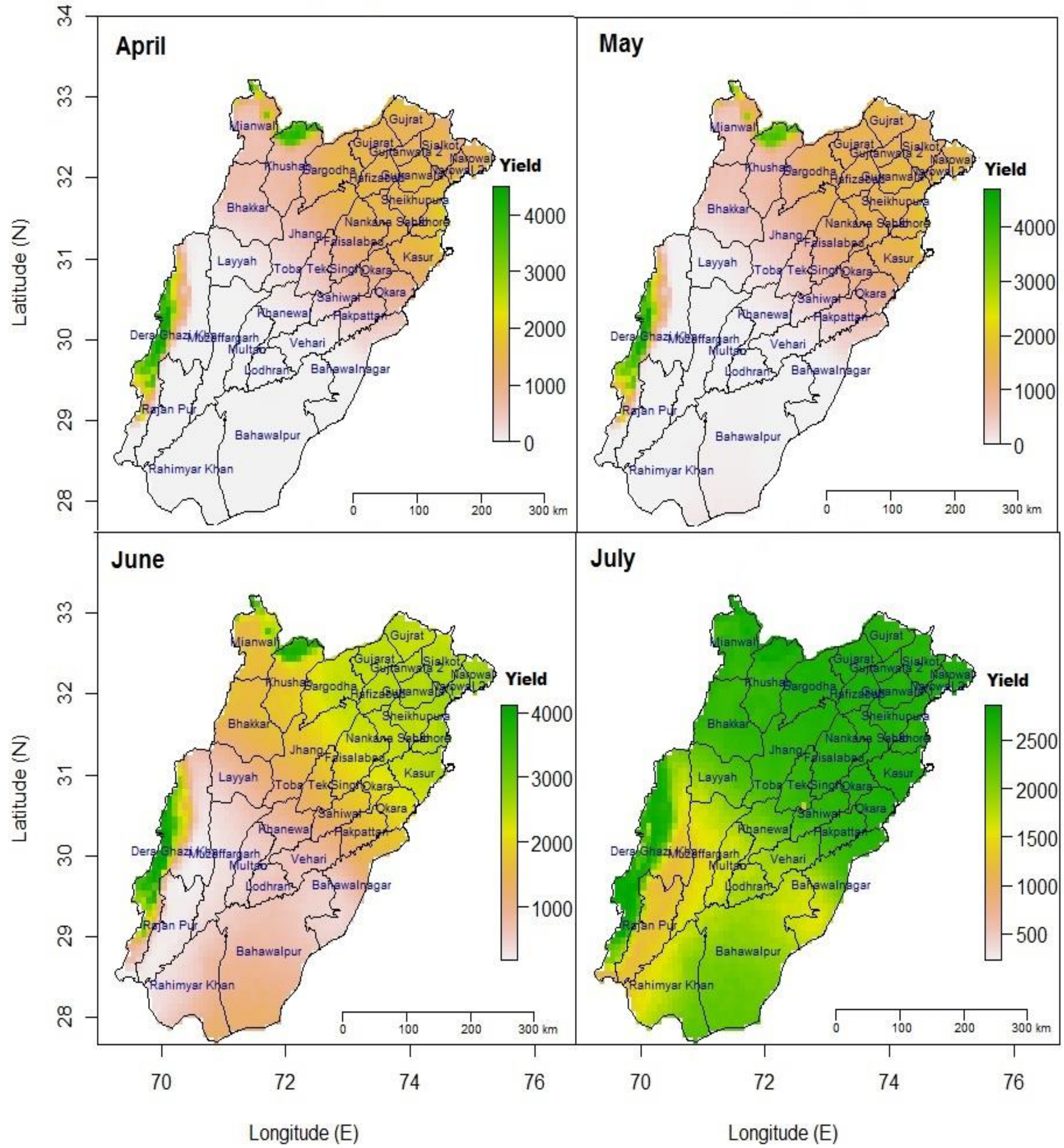

Figure 4.24: Cotton productivity (kg ha^{-1}) map of Punjab under late century scenario CMIP5 (RCP8.5) from April to July

CHAPTER-5

SUMMARY

The experimental study was commenced during the summer season of 2014 and 2015 to evaluate impact of climate change on Bt cotton cultivars using crop models and GIS tools. Three locational trial viz, Agronomic Research Area, University of Agriculture, Faisalabad (31.26 ^{o}N, 73.04 ^{o}E), Cotton Research Station (CRS) Sahiwal (30.40 ^{o}N, 73.06 ^{o}E) and Central Cotton Research Institute (CCRI.) Multan (30.12 ^{o}N, 71.26 ^{o}E) was conducted to collect field data required to run crop model. Fate of cotton crop was under future climate scenarios was determined with the help of seasonal analysis in CROPGRO-Cotton model and crop productivity maps in Geographic Information System. Outcomes of experiment are summarized as under:

- ❖ May sown crop produced 17.3% (140.65 vs 116.26) more plant height as compared to June sown crop due to longer crop duration and more radiation utilization. Maximum plant height (141.50 cm) was produced by cultivar FH-142 followed by cultivar MNH-886 (131.66 cm) while shorter plants height were observed in cultivar FH-114 (112.61 cm). Maximum plant height (133.70 cm) was produced at 250 kg ha^{-1} nitrogen level which was statistically at par (128.38 cm) with 200 kg ha^{-1} nitrogen while smaller plants (123.70 cm) were recorded in experimental plots where 150 kg ha^{-1} nitrogen was applied.
- ❖ More number of monopodial branches (3.11) were observed in May sown crop in comparison with June sown crop. Late planted significantly affected number of monopodial branches and minimum number of monopodial branches (1.72) were recorded in late sowing. Cultivar FH-114 produced maximum number of monopodial branches (3.22) while MNH-886 and FH-142 produced less number of monopodial branches (2.09 and 1.93) and both were at par with each other. Higher number of monopodial branches (2.74) were observed at 250 kg ha^{-1} nitrogen level which were at par with 200 kg N ha^{-1} during both growing seasons. Minimum number of monopodial branches (2.04) were recorded at 150 kg N ha^{-1}.
- ❖ Higher number of fruiting branches (19.45) were produced in May sown crop during both growing season at all locations that contributed to higher seed cotton yield. More fruiting branches (17.30) were produced by cultivar FH-142 followed by cultivar MNH-886

(16.04) while less number of sympodial branches (13.93) were produced by cultivar FH-114. Nitrogen level of 250 kg ha^{-1} produced 19% more fruiting branches than 150 kg ha^{-1} nitrogen level.

- ❖ Leaf Area Index increased progressively up to 130 days after sowing to attain its maximum value and then started decline towards end of the growing season. Comparatively, crop sown on 1st May showed significantly higher value (4.02) of leaf area index at all locations during both growing seasons than late sown cotton which attained less leaf area to land area ratio (2.76). Maximum LAI was recorded from cultivar FH-142 sown at Faisalabad and Sahiwal while cultivar MNH-886 produced maximum LAI at Multan site. On an average of all locations maximum LAI was recorded from cultivar FH-142 (3.59) followed by MNH-886 (3.47) and minimum was attained by cultivar FH-114 (3.10). Higher dose of nitrogen (250 kg ha^{-1}) produced higher Leaf area (3.85). Comparable value of LAI for lower level of nitrogen (150 kg ha^{-1}) was also minimum (2.84) due to less vegetative growth.
- ❖ Maximum LAD (279.27 days) was recorded in May sown crop while minimum LAD (173.41 days) was recorded in June sown crop. Higher leaf area duration (232.46 days) was computed from FH-142 followed by MNH-886 (240.93 days) whereas lower LAD (205.62 days) was observed from FH-114. Nitrogen rate of 250 kg ha^{-1} showed maximum LAD (261.51 days) followed by 200 kg N ha^{-1} (232.38 days) and comparatively minimum LAD (185.13 days) was recorded where 150 kg N ha^{-1} was applied. FH-142 with 250 kg N ha^{-1} attained higher leaf area duration (295.82 days and 286.04 days) followed by MNH-886 which is statistically at par while FH-114 attained lower LAD (171.95 days and 162.08 days) during 2014 and 2015 respectively at Sahiwal. Crop sown in the month of May performed well and achieved higher LAD (329.40 days and 312.64 days) with nitrogen dose of 250 kg ha^{-1} as compared to crop sown in the month of June that produced lower LAD (121.88 days and 157.89 days) during 2015 at Sahiwal and 2014 at Multan respectively.
- ❖ May sown cotton produced higher TDM (11880.16 kg ha^{-1}) during both growth season at all locations and lower TDM (8454.83 kg ha^{-1}) was recorded in June sown crop. Maximum TDM (10409 kg ha^{-1}) was recorded from cultivar FH-142 followed by cultivar MNH-886 (10655.66 kg ha^{-1}). Comparatively, minimum TDM was attained by cultivar FH-114

(9437.83 kg ha^{-1}). Higher dry matter accumulation (11525.66 kg ha^{-1}) was observed from experimental plots having 250 kg N ha^{-1} while lower dose of 150 kg N ha^{-1} contributed less vegetation and ultimately less dry matter accumulation (8661.33 kg ha^{-1}).

- May sown crop in 2014 showed progressive crop growth rate by 31.9% and 24.8% at Faisalabad, 33.3% and 26.4% at Sahiwal and 14.3% and 25% at Multan during 2014 and 2015 respectively due to favorable climatic conditions as compared to June sown crop. On an average of all locations, cultivar FH-142 attained maximum CGR (8.78 g m^{-2} day^{-1}) followed by MNH-886 and minimum CGR (7.80 g m^{-2} day^{-1}) was observed from cultivar FH-114. Similar trend was shown by all cultivars during both growing season (2014 and 2015). Mean CGR at 150, 200 and 250 kg N ha^{-1} was 7.17, 8.52 and 9.51 gm^{-2} day^{-1}, respectively.
- June sown crop attained 19.9% higher NAR (5.22 g m^{-2} day^{-1}) in comparison with May sown crop where NAR was less (4.18 g m^{-2} day^{-1}). Maximum NAR (4.99 g m^{-2} day^{-1}) was recorded from cultivar FH-114 whereas minimum NAR (4.48 g m^{-2} day^{-1}) was observed from cultivar FH-142. Net assimilation rate was lower at higher dose of nitrogen while higher at lower dose of nitrogen.
- May sown crop produced more number of opened bolls (28.65). Comparatively, less number of opened bolls (18.68) were produced by June sown crop. Cultivar FH-114 produced higher number of opened bolls (25.64) which was significantly more in number than medium maturing cultivars i.e. MNH-886 (22.13) and FH-142 (19.20). Nitrogen rate of 250 kg ha^{-1} conquered higher number (24.89) of opened bolls per plant whereas lower number (21.86) of opened bolls per plant were attained where nitrogen rate of 150 kg ha^{-1} was applied on an average of all locations.
- Average boll weight of May sown crop was higher (3.25 g) than late sown crop (2.66 g). Although total number of bolls per plant were higher on FH-114, however average boll weight was lower for this cultivar. Overall average bases, it is clear that FH-142 produced higher boll weight (3.24 g) followed by MNH-886 (3.08 g) and less boll weight (2.53 g) was produced by cultivar FH-114 during both growing seasons. Nitrogen dose of 250 kg ha^{-1} produced maximum boll weight (3.11 g) and nitrogen rate of 150 kg N ha^{-1} produced minimum boll weight (2.78 g).

- A statistically non-significant trend was observed for sowing dates at all locations during 1st year of experiment while in 2015, significant difference among sowing dates was observed at Sahiwal where higher 100-seed weight (6.90 g) was observed in May sown as compared to June sown crop (6.47 g). On an average, maximum SI (7.12 g) was observed from MNH-886 and minimum SI (5.86 g) was observed from FH-142. Nitrogen rates non-significantly affected 100-seed weight at all locations except 2nd year experiment at Sahiwal where maximum weight of 100-seeds (6.90 g) was recorded at nitrogen dose of 250 kg ha^{-1} during 2015.
- **S**eed cotton yield was 43% higher in May sown crop than June sown crop. At Faisalabad and Sahiwal, cultivar FH-142 produced maximum seed cotton yield. At Multan, cultivar MNH-886 produced highest seed cotton yield. On an average of all locations, cultivar FH-142 produced higher SCY (2937.16 kg ha^{-1}) while cultivar FH-114 produced lowest SCY (2421.71 kg ha^{-1}). Optimum level of nitrogen at rate of 200 kg ha^{-1} increased seed cotton yield (2836.50 kg ha^{-1}) compared to the less seed cotton yield (2386.93 kg ha^{-1}) with lowest nitrogen level of 150 kg ha^{-1}.
- Maximum GOT (42.03%) was recorded in May sown crop, whereas minimum GOT (4.15%) was recorded in June sown crop. Highest GOT was recorded from cultivar FH-142 at Faisalabad and Sahiwal, whereas cultivar MNH-886 gave highest GOT at Multan. On an average of all locations, cultivar FH-142 performed best and highest GOT was observed (39.05%). Comparatively, less GOT (42.87%) was produced by cultivar FH-114 at all locations. Nitrogen rates significantly affected GOT at all locations expect 1st year experiment at Faisalabad and Sahiwal and 2nd year experiment at Sahiwal. Maximum GOT was observed where 250 kg N ha^{-1} was applied while minimum GOT was attained where 150 kg ha^{-1} was applied.
- Micronaire value for May sown crop was higher (4.56) that showed a good fiber fineness and micronaire value for June sown crop was lower that indicated lower (3.52) fiber fineness. Cultivar FH-142 produced higher fiber fineness (4.18) in comparison with FH-114 where less fiber fineness (3.96) was observed. Nitrogen rate of 250 kg ha^{-1} gave higher micronaire (4.33) as compared to nitrogen rate of 150 kg ha^{-1} which produced lower micronaire (3.80) and poor quality fiber.

- Higher fiber length (24.26 mm) was observed in May sown crop and lower length of fiber (24.04 mm) was recorded in June sown crop. Longer fiber length (25.83 mm) was contributed by 250 kg ha^{-1} nitrogen followed by optimum dose and shorter fiber length was added by 150 kg ha^{-1} nitrogen.
- May sown crop gave higher fiber strength (29.99 g/tex) and crop sown late in the month of June gave lower fiber strength (28.58 g/tex). Experimental results depicted that more fiber strength (29.86 g/tex) was contributed by 250 kg ha^{-1} nitrogen followed by optimum dose and shorter fiber strength (28.53 g/tex) was added by 150 kg ha^{-1} nitrogen.
- May sown crop faced insignificant temperature during early days of crop growth that depressed plant respiration and enhanced photosynthesis rate and more 15% RUE_{TDM} (1.33 g MJ^{-1}). Comparatively, June sown crop lowered RUE_{TDM} (1.13 g MJ^{-1}) due to raised level in temperatures. Higher radiation use efficiency was recorded by FH-142 at Faisalabad and Sahiwal and radiation utilization efficiency by MNH-886 was higher at Multan. On an average of all locations, FH-142 performed well and maximum RUE_{TDM} (1.26 g MJ^{-1}) was computed from FH-142 followed by MNH-886 (1.25 g MJ^{-1}) and minimum RUE (1.17 g MJ^{-1}) was computed from FH-114. Highest dose of nitrogen increased RUE_{TDM} by 16.8% (1.31g MJ^{-1}) compared to the lower dose of nitrogen where less RUE (1.19 g MJ^{-1}) was computed.
- Sowing dates significantly affected radiation use efficiency for seed cotton yield at all locations. Comparatively, Radiation use efficiency of May sown crop was higher (0.37 g MJ^{-1}) to convert resources into final yield than June sown crop having less radiation utilization efficiency (0.26 g MJ^{-1}). Higher radiation use efficiency was recorded by FH-142 at Faisalabad and Sahiwal and radiation utilization efficiency by MNH-886 was higher at Multan. On an average of all locations, FH-142 performed well and maximum RUE_{YIELD} (0.34 g MJ^{-1}) was computed from FH-142 followed by MNH-886 and minimum RUE (0.28 g MJ^{-1}) was computed from FH-114. Highest dose of nitrogen increased RUE_{YIELD} by 16.8% (1.31 g MJ^{-1}) compared to the lower dose of nitrogen where less RUE (1.19 g MJ^{-1}) was computed.
- CROPGRO-Cotton under DSSAT model was run to forecast growth, development and seed cotton yield of cotton sown in the month of May and June. After model calibration with specific dataset, model simulated phenology, development and seed-cotton yield of

three cotton cultivars reasonably good. Model was checked for its validation with second year crop data.

- Calibration data revealed that anthesis days were one day higher by model as compared to observed anthesis days. Less root mean square error (0.57, 0.81, 0.81) was computed for cultivars FH-114, FH-142 and MNH-886. Index of agreement (d) of both sowing was greater than 0.80 for all experimental sites. Root mean square error (RMSE) of 1st May and 1st June sown crop was ranged from 1.15 to 1.73 and 1.15 to 1.69 respectively during model validation with second year data. The d value of 1st May and 1st June sown crop was higher than 0.80 for all locations except 1st May sown crop at Sahiwal where calculated d value was 0.74.
- Model simulated same number of days for maturity (149) than the observed ones for FH-142 while 3-4 days difference for cultivars FH-114 and MNH-886 having RMSE of 6.92, 0 and 4.12 days for cultivars FH-114, FH-142 and MNH-886. RMSE of 1st May and 1st June sown crop was between 1.85 to 2.40 and 1.69 to 2.72 respectively during 2015. The d value of 1st May and 1st June sown crop was greater than 0.80 for Faisalabad and Sahiwal except for Multan where calculated d value was greater than 0.70.
- Calibrated values of leaf area index were 3.97 (observed) and 4.32 (simulated) having root mean square error of 0.39 for cultivar FH-114; 4.42 (observed) 4.28 (simulated) having RMSE of 0.23 for cultivar FH-142; 4.36 (observed) and 4.67 (simulated) with RMSE of 0.40 for cultivar MNH-886. Root mean square error of model evaluation results ranged between 0.37 to 0.62 and 0.48 to 0.61 for 1st May and 1st June sown crop respectively while d value was greater than 0.70. RMSE of 1st May and 1st June sown crop was between 0.21 to 0.61 and 0.40 to 0.51 respectively during 2015. The d value of 1st May and 1st June sown crop was greater than 0.75 for all locations except June sown crop at Sahiwal where calculated d value was greater than 0.70.
- Overall calibrated values of total dry matter were 11608 kg ha^{-1} (observed) and 11838 kg ha^{-1} (simulated) with RMSE 273.54 kg ha^{-1} for cultivar FH-114; 12691 kg ha^{-1} (observed) and 12390 kg ha^{-1} (simulated) having root mean square error of 407.28 kg ha^{-1} for cultivar FH-142; 12607 kg ha^{-1} (observed) and 12062 kg ha^{-1} (simulated) having RMSE of 581.50 kg ha^{-1} for cultivar MNH-886. RMSE of 1st May and 1st June sown crop was between 499

to 573 and 512 to 562 respectively during 2015 while d value of 1st May and 1st June sown crop was greater than 0.90 for all locations.

- Overall calibrated values for seed cotton yield were 3280 kg ha^{-1} (observed) and 3219 kg ha^{-1} (simulated) having RMSE of 153.27 kg ha^{-1} for cultivar FH-114; 4195 kg ha^{-1} (observed) and 3903 kg ha^{-1} (simulated) having root mean square error of 448.40 kg ha^{-1}; 3601 kg ha^{-1} (observed) 3259 kg ha^{-1} (simulated) with RMSE of 401.01 kg ha^{-1}. RMSE of 1st May and 1st June sown crop was between 301 to 357 and 177 to 422 respectively during 2015 while d value of 1st May and 1st June sown crop was less than 0.70 for all locations expect for 1st May sown crop at Faisalabad and Multan having d value greater than 0.80.
- Model was run to evaluate crop under various scenarios of changed climate at all three. Locations by providing 30 years historic past climate data from 1984-2015. Model results showed that in early century (till 2039), there will be 16% yield loss under 1.7°C rise in temperature, 460 ppm CO_2 and 44.4% more rainfall at Faisalabad; 23% yield reduction under 1.7°C rise in temperature, 460 ppm CO_2 and 37.1% more rainfall at Sahiwal and 20% yield loss under 1.9°C rise in temperature, 460 ppm CO_2 and 105% more rainfall at Multan. In mid century (till 2069), there will be 33% yield loss under 7°C rise in temperature, 560 ppm CO_2 and 55.5% more rainfall at Faisalabad; 34% yield reduction under 3.7°C rise in temperature, 560 ppm CO_2 and 48.6% more rainfall at Sahiwal and 32% yield loss under 4.2°C rise in temperature, 560 ppm CO_2 and 118% more rainfall at Multan. In late century (till 2100), Model results showed that there will be 45% yield loss under 7°C rise in temperature, 660 ppm CO_2 and 77.7% more rainfall at Faisalabad; 36% yield reduction under 7°C rise in temperature, 660 ppm CO_2 and 71.4% more rainfall at Sahiwal and 35% yield loss under 7.6°C rise in temperature, 660 ppm CO_2 and 165% more rainfall at Multan.
- Strategy analysis showed that timely sown of cotton cultivar FH-142 in May with 200 kg N ha^{-1} can be viable option to get maximum yield at Faisalabad and Sahiwal and while MNH-886 sown on 1st May at Multan with 200 kg N ha^{-1} can perform best under future changing climate.
- GIS analysis showed that one month late sowing of crop in the month of June would be best to obtain higher seed cotton (> 4000 kg ha^{-1}) yield in whole upper Punjab and some

parts of central Punjab whereas yield would be around 2000 to 3000 kg ha^{-1} in southern Punjab if crop would be sown in the month of June.

- Dera Gazi Khan, Mianwali and Khushab districts have potential of higher seed cotton yield under 2°C rise in temperature in future. GIS maps with Metamodel showed similar results along with Sahiwal, Okara and Pakpatthan as potential districts for future cotton in Punjab.

CONCLUSION

Cultivar FH-142 with nitrogen rate of 200 kg ha^{-1} performed well in growth and development under agro-climatic conditions of Faisalabad and Sahiwal while cultivar MNH-886 with nitrogen rate of 200 kg ha^{-1} performed well under Multan conditions sown on 1st May. CROPGRO under DSSAT Model calibrated and validated well for all locations. Under future climate, 23% in Faisalabad, 4.32% in Sahiwal and 14.89% yield in Multan will be reduced in early century (till 2039) due to 2°C rise in temperature with 20% less rainfall having an elevated CO_2 level of 460 ppm. Strategy analysis showed that timely sown cotton cultivar FH-142 at Faisalabad and Sahiwal and MNH-886 at Multan in month of May with 200 kg N ha^{-1} can be viable option to get maximum yield. Model can be helpful tool to predict crop yield under future climate to develop site specific adaptation strategies for adjustment of sowing dates, irrigation, fertilizer with better management practices. GIS analysis further concluded that one month late sowing of crop in the month of June would be best to obtain higher seed cotton (> 4000 kg ha^{-1}) yield in whole upper Punjab and some parts of central Punjab whereas yield would be around 2000 to 3000 kg ha^{-1} in southern Punjab if crop would be sown in the month of June. Spatial analysis with Weather generator showed that cotton yield will reduce in future all over Punjab and Dera Gazi Khan, Mianwali and Khushab districts have potential of higher seed cotton yield under 2°C rise in temperature in future. GIS maps with Metamodel showed similar results along with Sahiwal, Okara and Pakpatthan as potential districts for future cotton in Punjab.

FUTURE THRUSTS

- Yield Forecasting with Integration of Crop Models and Remote Sensing should be focused more for more precise farming.
- Unmanned Aerial Vehicles (UAVs) for crop management should be consider for a sustainable crop production with proper resource utilization.
- Monitoring Crop Shift and rezoning of agro-ecological zones should be done in future studies for better cotton production.

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