EFFECT OF PERIODICAL CO_2 ENRICHMENT ON WHEAT *CV.* PBW 343 THROUGH FIELD AND SIMULATION STUDY

Ph. D. THESIS

by

SUNIL KUMAR DUBEY

DEPARTMENT OF WATER RESOURCES DEVELOPMENT & MANAGEMENT
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE - 247 667, INDIA
DECEMBER, 2017

EFFECT OF PERIODICAL CO_2 ENRICHMENT ON WHEAT *CV.* PBW 343 THROUGH FIELD AND SIMULATION STUDY

A THESIS

Submitted in partial fulfilment of the requirements for the award of the degree

of

DOCTOR OF PHILOSOPHY

in

WATER RESOURCES DEVELOPMENT AND MANAGEMENT

by

SUNIL KUMAR DUBEY

DEPARTMENT OF WATER RESOURCES DEVELOPMENT & MANAGEMENT
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE - 247 667 (INDIA)

DECEMBER, 2017

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"EFFECT OF PERIODICAL CO_2 ENRICHMENT ON WHEAT *cv.* PBW 343 THROUGH FIELD AND SIMULATION STUDY"** in partial fulfilment of the requirement for the award of the Degree of Doctor of Philosophy and submitted in the Department of Water Resources Development and Management of the Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during a period from July, 2011 to December, 2017 under the supervision of Dr. S. K. Tripathi, Professor, Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, India.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

(SUNIL KUMAR DUBEY)

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

S.K. Tripathi
Supervisor

The Ph.D. Viva-Voce Examination of Mr. Sunil Kumar Dubey, Research Scholar, has been held on 21st June, 2018.

Chairman, SRC **Signature of External Examiner**

This is to certify that student has made all the corrections in the thesis.

Signature of Supervisor (s) **Head of the Department**
Date:

ABSTRACT

The global population is rising and demand for protein-rich diets are increasing pressure to maximize the agricultural productivity. At the same time rising atmospheric CO_2 altering the global temperature and precipitation patterns, are challenges to agricultural productivity. It has already been proved that a rising CO_2 provides a unique opportunity to increase the productivity of C_3 crops by improving the photosynthetic activity in the plants. Thus, under ample supply of CO_2 condition the carboxylation process is accelerated and resulting in increased photosynthesis which in turn enhances the plant growth. This phenomena is termed as "Carbon Dioxide Fertilization Effect" and defined as the enhancement of the growth of plants as a result of increased atmospheric CO_2 concentration.

Wheat (*Triticum aestivum* L. and related species) is an important crop grown over the entire globe. It covers more than 25% of global cropland and contributing about 21% of calories and 22% of protein to the human food supply. Even after such a coverage and dependency of people globally, the observed average yield is well below the potential gains. There is ample room for improving the productivity by utilizing the rising atmospheric CO_2. As of now only a fraction of available genotype of wheat has been tested for CO_2 responsiveness.

In order to evaluate the response of rising CO_2 on wheat an experimental field study was conducted in Haridwar district of Uttrakhand State (India) during the years 2011-12 and 2012-13. Wheat cultivar PBW 343 was taken as a test genotype using locally designed low-cost per unit area Open Top Chamber (OTC) experiments. The study was undertaken with the specific objectives to (1) assess the effect of periodical CO_2 enrichment on microclimatic change in wheat crop. (2) Evaluate the effect of periodical CO_2 enrichment on growth, development, yield and quality of wheat crop. (3) Calibration and evaluation of the DSSAT CERES-Wheat model using field experimental data. (4) Suggestion for the agronomic ways and means to improve the productivity of wheat under changing climate.

Field experiment was laid out in Randomized Block Design (RBD) with 4 treatments of CO_2 enrichment and 3 replications during *Rabi* season (November-April) of the years 2011-12 and 2012-13. Treatment includes -Control (without CO_2 enrichment), 700 ± 50 ppm CO_2 (enrichment once a week, 700 ± 50 ppm CO_2 (enrichment twice in a week) and 700 ± 50 ppm CO_2 (enrichment thrice in a week) on the demonstration farm of the Department of Water Resources Development

and Management, Indian Institute of Technology Roorkee, Uttrakhand (India). Fire extinguishing CO_2 cylinders were used for CO_2 enrichment. IPCC projections for the years 2050 (550 ppm) and 2100 (750 ppm) were used as a guideline for CO_2 enrichment in wheat crop. Observations were recorded for the changes in microclimate, plant growth and development attributes, yield and yield attributes, physical and chemical quality components of grain.

For calibration of DSSAT CERES Wheat model under the soil climatic condition of Roorkee, a separate field experiment was conducted using cultivar *cv*. PBW-343 with recommended package of practices during the year 2013-14 with four different dates of sowing *i.e.* 15th Nov.; 22nd Nov.; 29th Nov. and 6th Dec. All the growth, yield and yield attributes were recorded for calibrating the CERES Wheat model. In order to derive the genetic coefficient, DSSAT CERES Wheat model was run iteratively by adjusting genetic coefficient values until the simulated and observed values were statistically significant.

Furthermore, the DSSAT CERES wheat model was evaluated by using results on growth, development and yield attributes obtained from different treatments of the field experiment conducted during the years 2011-12 and 2012-13. Actual soil parameters, weather parameters, and the crop management practices followed under different CO_2 enrichment treatments were used as the data input to run the model for different treatments. Genetic coefficient generated in the calibration process was used to run the model. The effect of CO_2 enrichment treatments on the growth, development and grain yield was simulated. The simulated values were statistically compared with the observed values. Various statistical techniques *i.e.* Root Mean Square Error, Normalized Root Mean Square Error, Mean Bias Error, Index of Agreement, Fractional Bias, Coefficient of determination and Percent Deviation etc. were adopted to evaluate the model outputs.

The CERES Wheat model was also used to test the sustainability of experiment in the future scenario. For this purpose PRECIS-regional climate model derived weather data were used for simulating the wheat productivity during the period of 2015-2030 keeping in view the agro technological advances. Further, to suggest the agronomic adoptions for improving the wheat productivity in the future (2015-2030) changing climate, the model was run by taking five dates of sowing and five nitrogen doses under four CO_2 scenarios.

The periodical CO_2 enrichment under field condition was employed using locally available low-cost materials (Fire extinguishing quality CO_2, iron rods and normal plastic sheet) as an alternative to FACE and OTC techniques. Further, the CO_2 has been used to assess the climate change impact and its fertilization effect on wheat productivity. The CO_2 enrichment effect on a particular wheat variety (*cv*. PBW 343) has been established through a two year experiments. Similar, study can be replicated for a longer period to test the validity of experiment for various genotype of wheat at different agroclimatic regions of India.

Results obtained from the field experiment are summarized as follows:

1. A marginal increase of 0.2-0.5 ºC in leaf temperature, within canopy temperature and above canopy temperature was noticed among the CO_2 treated plots. Practically there was no abnormality shown by the crop with such a change in temperature, probably this increase was purely temporary in nature as the crop was grown under the open field condition. The average ambient CO_2 concentration in the experimental plot was recorded as 309 ppm during 2011-12 and 319 ppm during 2012-13. The result showed that the CO_2 level rose to about 770 ± 10 ppm at the time of application which subsided to 560±10ppm within 15 minutes of application and further subsided to normal equivalent to ambient within 20 minutes.

2. The CO_2 enrichment treatments of wheat crop *cv.* PBW-343 recorded significant increase in plant height, tiller count, leaf length and width, dry matter, LAI, flag leaf area, leaf area duration, % effective tiller, grain weight /plant (g), grain test weight (g), grain yield, straw yield and biological yield though the CO_2 enrichment effect was insignificant for ear emergence, anthesis, and flowering, no. of grain/spike, harvest index, grain length and width. Grain Protein & Nitrogen content were significantly decreased and carbohydrate content was increased due to CO_2 enrichment. Other macro nutrient content such as K, Mg and S increased and P, Ca were decreased, though the change was insignificant.

3. The calibration of the DSSAT CERES wheat model using field experimental data of four dates of sowing conducted during 2013-14 shows that the variation of observed and simulated growth, development and yield parameters are within the acceptable range. Thus, the DSSAT CERES wheat model output is acceptable to soil climatic condition of Roorkee.

4. The DSSAT CERES wheat model was evaluated using field experimental data of four CO_2 enrichment treatments conducted during the years 2011-12 and 2012-13. Model simulated growth and yield parameters are at par with actual experiment. This proves that the model could be effectively used for simulating field experiment of Wheat *cv*. PBW 343.

5. The DSSAT CERES Wheat simulation during the years 2015-2030 showed that the yield will decline with the advancing of climate change but CO_2 intervention will compensate the loss in yield due to higher temperature and erratic rainfall pattern (climate change).

6. The DSSAT was used to develop the adaptation strategies for the future (2015-2030) under the climate change and higher CO_2 scenarios. The result showed that the better yield can be obtained by sowing the wheat between 14-28 November, and adopting the nitrogen application between 100-120 kg/ha.

Study reveals that the response of periodical enrichment of CO_2 on wheat *cv*. PBW-343 under the soil climatic conditions of Roorkee (Haridwar, Uttarakhand, India) is beneficial to increase its productivity.

ACKNOWLEDGMENTS

I owe my deepest gratitude and consider it a greatest privilege to express my heartfelt appreciation to the major advisor and chairman of my advisory committee Prof. S.K. Tripathi, Department of Water Resource Development and Management, Indian Institute of Technology Roorkee. For due this inspiring guidance, unending zeal, constant encouragement and constructive criticism, which are effectively orchestrated the total endeavor, not only limited to this work, but will take me long way in my life. The present work has been possible due to his ardent interest and invaluable suggestions. He has been my mentor to whom I am obliged for unconditional trust, support, patience and also freedom to voice my trivial questions. He has inculcated the belief to do the best.

In extent my cordial thanks and indebtedness to honorable members of my SRC committee, Head of Department Prof. S.K. Mishra, Chairman SRC Prof. Deepak Khare, Member Internal Dr. Ashish Pandey Associate Professor, External Member Prof. G.S. Randhawa Department of Biotechnology for their critical and productive discussions, cooperation, calm endurance, valuable suggestion and providing facilities during the course of investigation.

I am cordially grateful to other faculty members of Department of Water Resource Development and Management, IIT Roorkee, Prof. Nayan Sharma, Prof. U.C. Chaubey, Prof. M.L. Kansal, Prof. Gopal Chauhan, Emeritus Prof. D. Das for their support and encouragement. I express my sincere thanks to all staff members of the administrative office Mr. Soraj, Mr. Beer Singh, Mr. Baburam, Mr. Bijendra Singh, Mr. Akshat, Mr. Mukesh Kumar, and Mr. Anurag, Mr. Satpal, Mr. Subhash, Mr. Sanjeev for their kind support and all help rendered by them during my stay at IIT Roorkee.

I am immensely thankful to India Meteorology Department for providing the financial support/fellowship from the project Integrated Agro Advisory Service, which helps to carry out the work.

I took opportunity to record my thanks to Dr. S.S. Ray, Director, Mahalanobis National Crop Forecast Centre, Department of Agriculture Cooperation and Farmers

Welfare, Ministry of Agriculture and Farmers Welfare, Government of India for providing constant encouragement and support in completion of this work.

I am over whelmed with rejoice to avail this rare opportunity to evince my profound sense of indebtedness to my beloved father Sri Hari Prasad Dubey, mother Smt. Gayatri Devi, my beloved younger brother, Rahul Dubey, Rohit, Amit and Dev Prabhakar.

I woe a world of inner feeling and cordial thanks to my wife Smt. Shipra Dubey for her encouragement, support and creating pleasant environment during the course of investigation.

I took opportunity to record my thanks to my seniors Dr. G. Pranuthi, Ms. Reshu Yadav, Dr. Shalini Pareek, Dr. Surendra Chandaniha, Dr. Shakti Suryavanshi, Dr. Arvind Kumar Srivastav, Dr. Rituraj Shukla, Dr. Praveen Patil, Dr. Surendra Pal Singh, my colleagues Mr. Shyam Kumar, Mr. Navneet Kumar, Mr. Deepak Maurya, Mr. Anoop Shukla, Mr. Sandeep Shukla, Mr. Ankit Tiwari and many more friends helped me. If I do not list their names it is not for the lack of gratitude but for the lack of space, to all of them, I give my sincere thanks.

Without blessing almighty "God" these efforts could have remained a far-fetched dream and sheath of notes.

(Sunil Kumar Dubey)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

S. No.	Abbreviation	Expansion
1.	ANOVA	Analysis of Variance
2.	NOAA	National Oceanic and Atmospheric Administration, USA
3.	DSSAT	Decision Support System for Agro technology Transfer
4.	FAOSTAT	Statistics Division of Food and Agriculture Organization, UN
5.	CIMMYT	International Maize and Wheat Improvement Center, Mexico
6.	FAO	Food and Agriculture Organization, Rome, Italy
7.	DES	Department of Economics and Statistics, Govt. of India
8.	IITM	Indian Institute of Tropical Meteorology, Pune, India
9.	IMD	India Meteorological Department
10.	CERES	Crop Environment REsource Synthesis
11.	IPCC	Intergovernmental Panel on Climate Change
12.	CSM	Cropping System Model
13.	RCM	Regional Climate Model
14.	PRECIS	Providing REgional Climates for Impacts Studies
15.	WGP	Wheat Growing Period
16.	IGP	Indo Gangatic Plain Zone
17.	GHGs	Greenhouse gases
18.	CFC	Chlorofluorocarbon
19.	OTC	Open Top Chamber Experiments
20.	FACE	Free-Air Carbon dioxide Enrichment
21.	LAR	Leaf Area Ratio
22.	RGR	Relative Growth Rate
23.	NAR	Net Assimilation Rate
24.	SLW	Specific Leaf weight
25.	SLA	Specific Leaf Area
26.	LWR	Leaf Weight Ratio
27.	DAS	Days After Sowing
28.	msl	Mean Sea Level

29.	SO_2	Sulfur dioxide
30.	O_3	Ozone
31.	N	Nitrogen
32.	P	Phosphorus
33.	K	Potash
34.	Ca	Calcium
35.	Mg	Magnesium
36.	S	Sulphur

LIST OF ACRONYMS (DSSAT)

S. No	Abbreviation	Expansion
1.	Alb	Albedo Fraction
2.	BD	Bulk Density
3.	Beg Gr Fil	Beginning Grain Filling
4.	CEC	Cation Exchange Capacity
5.	DR	Drainage Rate
6.	EL	Evaporation Limit
7.	ET	Evapotranspiration
8.	FC	Field Capacity
9.	GDD	Growing Degree Days
10.	OC	Organic Carbon
11.	PAR	Photosynthetically Active Radiation
12.	pH	Concentration of Hydrogen Ion
13.	PWP	Permanent Wilting Point
14.	RO	Runoff Curve Number
15.	RUE	Radiation Use Efficiency
16.	SCS	Soil Conservation Service
17.	SP	Saturation Point

LIST OF UNITS

S. No.	Unit	Abbreviation
1.	°C	Degree Celsius
2.	cm	Centimeter
3.	Cmol kg^{-1}	Centimole units of energy per kilogram of soil
4.	gcm^{-2}	Gram per square centimetre
5.	kgs	Kilogram
6.	Kg ha^{-1}	Kilogram per hectare
7.	m	meter
8.	M ha	Million hectares
9.	MJ $m^{-2}day^{-1}$	Mega Joules per square meter per day
10.	Mt	Million Tones
11.	no. m^{-2}	Number per meter square
12.	ppm	Parts per million
13.	q h a^{-1}	Quintal per hectare
14.	t ha^{-1}	Ton per hectare
15.	N_2	Nitrogen
16.	OC	Organic carbon
17.	000ha	Thousand hectare
18.	'00 kg ha^{-1}	Hundred kilogram per hectare
19.	'000 T	Thousand ton
20.	@	At the rate
21.	µmol m^{-2} sec^{-1}	Micro mole per meter square per second
22.	mol m^{-2} sec^{-1}	Mole per meter square per second
23.	mg g^{-1}	Milligram per gram
24.	cm^3cm^{-3}	Cubic centimetre per centimetre cube

Chapter-1

INTRODUCTION

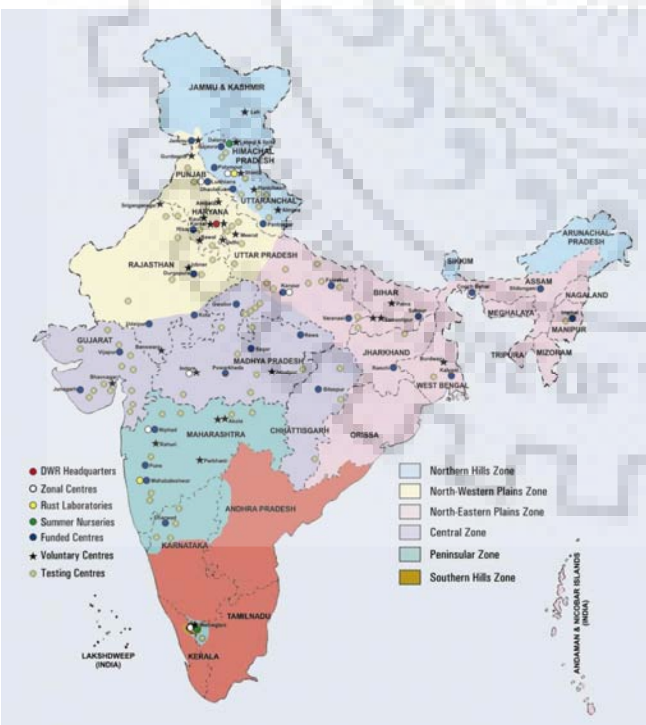
More than 50 % of the global plant- derived food energy is delivered by only three crops *i.e.* Wheat, Rice and Maize. Out of which Wheat (*Triticum aestivum* L. and related species) is the most important crop grown over the entire globe. Recent data summarized by the FAO indicate that wheat is harvested from > 25% of global cropland with total cultivated area of 221.6 M ha and production of 729.0 Mt, contributing about 21% of calories and 22% of protein to the human food supply (Hawkesford *et al.*, 2013). Asia continent contributes approximately 50 % of global Wheat area (102.0 M ha) and 40 % of the global production (315.7 Mt). In global context, India stand's first in term of area (14 % of world and 31 % of Asia continent) and second in production (13% of world and 30 %t of Asia's production). India occupies 31.2 M ha area and 94.5 Mt production with the average productivity of 3029.5 kg ha^{-1} (FAOSTAT, 2014).

Wheat is an annual C_3 plant of *Gramineae* family mostly grown in winter. It belongs to the genus *Triticum*. In the past there were 4 species of wheat, *viz*. *Triticum aestivum* (common Bread Wheat), *Triticum durum* (Macaroni wheat), *Triticum dicoccum* (Emmer Wheat) and *Triticum sphaerococcum* (Indian wheat) under cultivation in India. The *Triticum sphaerococcum* has now gone out of cultivation because of its low productivity and high susceptibility to diseases. Presently throughout the country only spring type wheat varieties are grown. Total share of *T. aestivum, T. durum* and *T. dicoccum* in Indian wheat production is 95%, 4% and 1%, respectively.

Cultivation of wheat in India dates back to more than 5000 years during the period of Indus valley civilization. At the time of independence, country was facing the shortage of wheat production. In order to meet the demand, wheat was imported from different wheat producing countries like USA under the Public Law 480 also known as "Food for Peace Act". Numerous reasons assigned for such low productivity were- tall growing & lodging prone varieties, poor and non-synchronous tillering, susceptibility to insect pest and diseases, sensitivity to temperature & photoperiod etc. In 1961 Government of India appointed a commission to review the possibility of increasing crop productivity with the available germplasm resources in different agro ecological zones of the country. Commission suggested various steps to make the country self-reliant in food grain production by emphasizing on rice and wheat crop. Nobel laureate Dr. Norman E. Borlaug "father of green revolution" developed a number of dwarf photo and thermo insensitive varieties of wheat at CIMMYT Mexico in 1964. Out of which, 'Lerma Rojo 64-A', 'Sonora 64' and 'PV 18' were found suitable to soil climatic conditions of India. These varieties were found to be nutrient and water demanding resistant to lodging.

The Government of India imported 18,000 tons seeds of 'Lerma Rojo 64-A' in 1966 for planting on about 0.4 M ha area in the country. As a result of this, a major breakthrough in wheat productivity and production was observed in the country. But consumers were not satisfied with the deep red colour-grains of these varieties and were reluctant to accept. This led to the selection of many promising genotypes like Kalyan Sona, Sonalika, Safed Lerma and Chhoti Lerma in 1967 under the leadership of Dr M.S. Swaminathan. The Kalyan Sona and Sonalika varieties became very popular among farmers in India because of their high yield, rust resistance, amber colour and adaptability to different soil and climatic conditions. Nearly 10 M ha area under high yielding varieties (HYV) was occupied by 1970 and made the 'Green Revolution' happen in the country. Since 1971, the wheat production scenario of the country got completely changed, once a deficient country became a surplus one (Crosson *et al.*, 1991).

In India, wheat cultivation ranges from tropical, sub-tropical to temperate zone from sea level to 3300 m altitude. The zone wise area and productivity of wheat in India is depicted in Figure 1.1.



- **Northern Hills Zone (NHZ):** Wheat growing area of 0.8 M ha and Productivity is 1664 kg ha^{-1}.
- **North Western Plain Zone (NWPZ):** Area 9.5 M ha. Productivity is 3940 kg ha^{-1}.
- **North Eastern Plain Zone (NEPZ):** Area again 9.5 M ha but Productivity is 2510 kg ha^{-1}.
- **Central Zone (CZ):** Area is about 4.5 M ha productivity is 2410 kg ha^{-1}.
- **Peninsular Zone (PZ):** Area is about 1.5 M ha and productivity is 2980 kg ha^{-1}.
- **Southern Hills Zone (SHZ):** Area is about 0.2 M ha and productivity is 1000 kg ha^{-1}.

Figure 1.1: Wheat growing zones in India
Source: (*http://agropedia.iitk.ac.in/content/wheat-growing-zones-india*

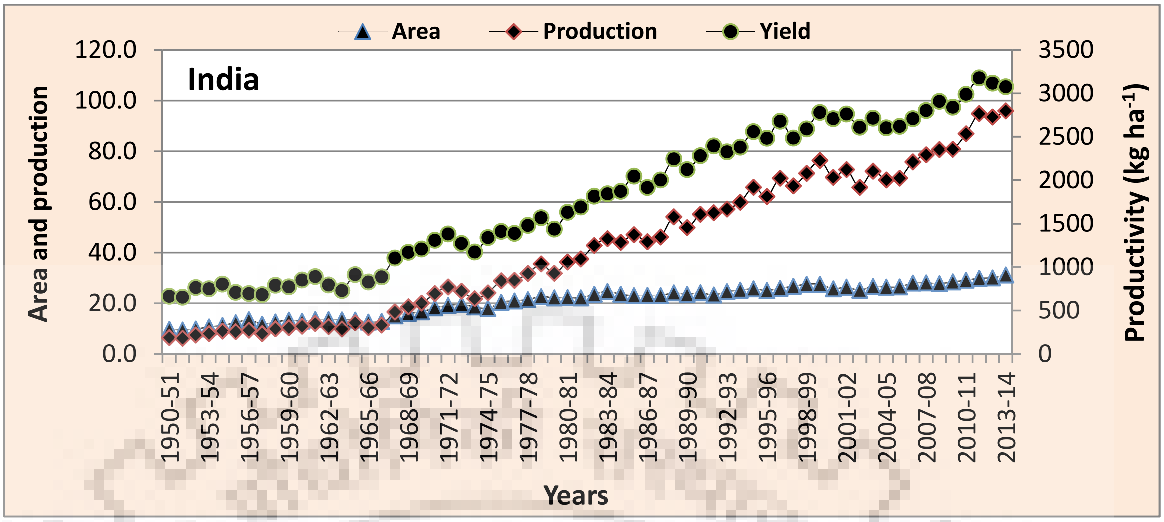


Figure 1.2a: Area (M ha), production (Mt), and productivity (kg ha^{-1}) of wheat in India

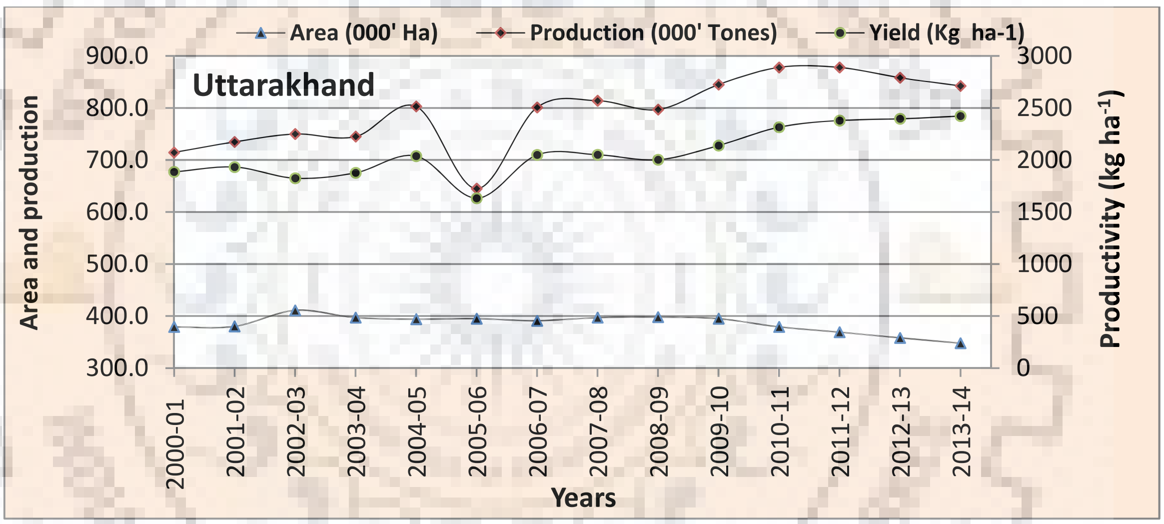


Figure 1.2b: Area ('000 ha), production ('000 T), and productivity (kg ha^{-1}) of wheat in Uttarakhand

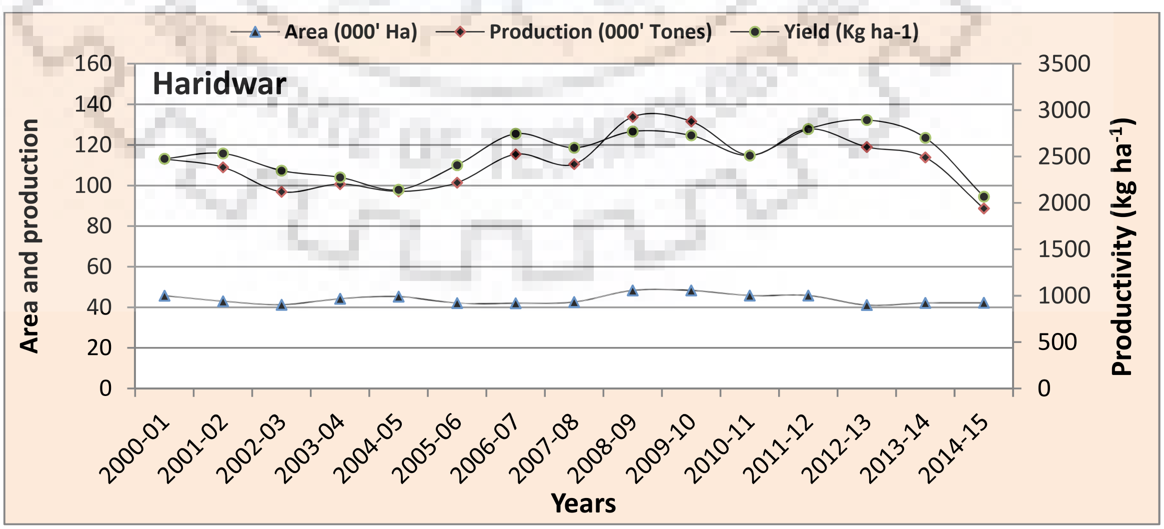


Figure 1.2c: Area ('000ha), production ('000 T), and productivity (kg ha^{-1}) of wheat in Haridwar

Major wheat producing states are- Uttar Pradesh (28.4 Mt), Punjab (16.5 Mt), Madhya Pradesh (15.6 Mt), Haryana (11.5 Mt), Bihar (5.3 Mt), Gujarat (2.6 Mt), West Bengal (0.9 Mt), Uttarakhand (0.8 Mt), Jammu and Kashmir (0.5 Mt), Jharkhand (0.3 Mt), Odisha (0.2 Mt) and Chhattisgarh (0.1 Mt). Area, production and productivity of wheat in India, Uttarakhand state (India) and Haridwar district (Uttarakhand) is presented in Figure 1.2a, 1.2b and 1.2c.

Decrease in productivity of wheat is observed at all the levels, be it the country (India), state (Uttarakhand) or district (Haridwar) and is a matter of great concern to the scientists, planners, administrators, managers and farmers (DES, 2014). A number of reasons could be assigned to this loss in productivity but the change in weather condition (rise in CO_2 levels & air temperature as well as erratic rainfall pattern) is often talked. Finding solution to arrest the productivity loss of wheat in the country is a great challenge to the agriculture scientist fraternity.

1.1 Global Scenario

The supply of food to meet the requirement of current global population, seems to be difficult in the face of a burgeoning population, increasing monetary stress, declining the availability of arable land and water as well as the changing climate especially the elevated temperature as well as uneven distribution of rainfall (Joshi *et al.*, 2011; Lobell *et al.*, 2011; Lobell *et al.*, 2012). With a world population of 9 billion by 2050, wheat demand is expected to rise by 1260 Mt. For this purpose, wheat productivity must increase at the rate of 1.7% instead of current level of <1%. After attaining the green revolution, yield in many countries is stagnant or decreasing due to the indiscriminate use of chemicals and poor soil fertility management. Countries like China, India and USA have sufficient scope to achieve the goal of projected demand through agronomic as well as genetic improvement (Hawkesford *et al.*, 2013). Increase in agricultural growth during last decades is attributable to the agronomic and genetic improvement (Conway and Barbier, 2013; Fan *et al.*, 2011; Pingali, 2012). Shrinking of cultivated area due to urbanization of the population, pose a challenge to agronomist for a breakthrough technology in improving production on reduced availability of land. Continued global population rise and changing climatic scenario are mounting pressure on scientists to solve this complex problem and developing cutting edge technology in crop production. As a result, scientists from different background are busy in solving this complex problem in their own way.

1.2 Extent of Climate Change

Over the past few decades the gaseous composition of the atmosphere has under gone significant changes due to anthropogenic activities resulting into increased emission of Green House Gases (GHGs) *viz.,* CO_2, CH_4 and N_2O. These gases trap outgoing infrared from the earth's surface and resulting into rise in temperature and altering the hydrological cycle and changing the precipitation pattern. The quantity of rainfall and its occurrence has also become more uncertain (Trenberth, 2011). In certain places, climatic extremes such as drought, floods, rainfall distribution and snow melt have increased. It has been projected to raise the sea level in the logical range of 0.5–2 m during the 21st century by assuming a 4°C or more change in temperature (Nicholls *et al*., 2011). Similarly, snow cover is also believed to be gradually decreasing (Callaghan *et al*., 2011). It is projected that the global average air temperature would rise by 1.9-4.6 ^{0}C over the next 100 years. During pre-industrial period the average CO_2 concentration was nearly 280 ppm now has reached up to 400 ppm and expected to touch the level of 500 ppm by 2030. The increasing concentration of CO_2 in the atmosphere may impact positively for some crops, but the extent needs to assess.

According to NOAA report "global average CO_2 concentration at the time of pre-industrial revolution (19th century) was about 280 ppm. It is reported that during the Ice Age (800,000 years ago) the atmospheric CO_2 fluctuated between 180 ppm to 280 ppm. In the past ten years (2005- 2014), the average annual rate of increase in CO_2 is 2.11 ppm per year. Current global average CO_2 concentration is 404 ppm (Anonymous, 2016) and is projected to increase by 550 ppm in 2050 and 750 ppm in 2100 while global concentration of GHGs is expected to reach approximately 685 ppm CO_2-equivalent by mid-century and more than 1000 ppm by 2100 (Marchal *et al*., 2011).

CO_2 is the chief component of photosynthesis in plant. It enters the plant through leaf stomata and evolves in the photosynthetic process. Research on CO_2 and its role in photosynthesis as well as the plant growth and development was initiated by Stephane Hales in year 1727 and reported that the green parts of the plant get nourished through their leaves in the presence of sunlight. In the third quarter of 18th century Priestley demonstrated the gas exchange during the photosynthesis. An Austrian botanist, Ingenhauz in 1979, demonstrated that plants purify the air only in presence of light. The green part of plant produces purifying agent (O_2) only, while non-green part produces pollutant (CO_2). Jean Senebier in 1800 recognized the O_2 liberated from the plant during photosynthesis comes from CO_2 which was absorbed by plant. Liebig in year 1840 for first time reported that carbon, an essential element in plant was obtained from CO_2. De Saussure in 1804 noted the faster growth in Pea plant with an elevated atmospheric CO_2. Sachs in 1887 reported that green chloroplast, were the organ where CO_2 was used up and O_2 was liberated and starch was the first visible product of photosynthesis. Lundegardh in year 1920-1923 carried out CO_2 enrichment experiment on field crops (Sugar beet and Oat) became the first scientist to record 16% increase in sugar beet root production with 15% increase in atmospheric CO_2 whereas, the Oat production increased by 30 % on doubling of CO_2 from 282 to 564 ppm.

The elevated atmospheric CO_2 positively affected the crop growth and productivity, both in terms of quantity and quality probably by increased photosynthesis, nutrient and water use efficiency, is termed as Carbon dioxide fertilization (Attavanich and McCarl, 2014). The Carbon dioxide fertilization effect is defined as "the enhancement of the growth of plants as a result of increased atmospheric CO_2 concentration" (Franks *et al*., 2013; Reich *et al*., 2014). Carbon dioxide, water, sunshine and chlorophyll are the primary inputs of photosynthetic activity in the plants. Majority of the field crop plants, including wheat, fixes CO_2 via C_3 pathway. At elevated CO_2 the carboxylation process is accelerated in C_3 plants which in turn enhance the process of photosynthesis (Seneweera *et al.,* 2005a). When C_3 plants, such as wheat, are exposed to high CO_2 concentration, the net photosynthesis rate of the leaves is accelerated due to both enrichment of substrate CO_2 and inhibition of photorespiration by increased concentration of CO_2 (Agrawal, 2012; Busch *et al*., 2013). The beneficial effects of increased concentration of atmospheric CO_2 on wheat plants included the reduction in stomatal conductance and transpiration, improved water-use efficiency, increased rates of photosynthesis and light-use efficiency (Bunce, 2013; Dong *et al*., 2016).These findings came from the studies undertaken in controlled environments or enclosures (Amthor, 2001; Dubey *et al*., 2015a).

Amthor (2001) and Kimball (1983) critically reviewed a large number of results reported on wheat plants grown with enriched CO_2 in the green houses, laboratory chambers, open top chambers, closed top chambers and free air CO_2 enrichment (FACE) and reported the increased grain yield ranging from 4-43%. Laboratory and controlled condition studies on wheat conducted worldwide proved that the elevated CO_2 level not only enhance the rate of photosynthesis (Pal *et al.,* 2005) but also increase the number of tillers, plant biomass and grain yield depending upon the genotype, climate, and management practice (Uprety *et al*., 2009). The elevated temperature regime of crop shortened the growing period of wheat that lead to decreased yields whereas the elevated CO_2 increased the yields (Dubey *et al*., 2014; Schmid *et al.*, 2015; Wheeler *et al*., 1996; Brown and Rosenberg, 1999; Asseng *et al*., 2011, Asseng *et al*., 2015; Pal *et al*., 2012b; Pal, *et al*., 2012d).

C_3 plant shows a significant stimulation of net CO_2 assimilation under short-term CO_2 enrichment with accumulation of carbohydrates (Bunce, 2013). These may be involved in the down-regulation of genes coding for photosynthetic enzymes (*e.g.* RBCS), soluble proteins and therefore of photosynthetic capacity (Spalding 1994; Moore *et al*., 1998, Moore *et al*., 1999). Short term exposure of elevated levels of CO_2 is reported to stimulate the net photosynthetic rate in C_3 plants because the existing CO_2 concentration in the atmosphere is insufficient for its supply to them Rubisco (ribulose-1, 5-bisphosphate carboxylase/oxygenase) (Drake *et al*., 1997). Increment in specific leaf area, total carbohydrate and total chlorophyll content was noticed in *Vigna radiata* and *Vigna unguiculata* when the plant was exposed to 2% and 3% CO_2 for 5 and 10 minutes in controlled environment chamber thrice a week for 4 weeks (Hamid *et al.* 2009). From the critical review of researches it has been observed that almost all these experimental results were reported from the studies undertaken either in chamber or limited environmental condition for shorter periods and did not cover the full life cycle of the plant. In view of this the present study was framed out by undertaking wheat crop trials with elevated CO_2 in open field condition.

It is important to evaluate the study before implementing on the ground for this purpose simulation models are the best tools which can answer the "what if". Crop growth simulation models are developed to show the complex interaction of agronomic, environmental and hydrologic factors on crop growth. Simulation models are a means to analyze the potential effects of climate change on crop growth, but testing model performance against measured data under changing climate scenarios is essential for such an analysis to be meaningful.

To simulate the yield of wheat crop under numerous scenario's various crop simulation models like DSSAT, Info Crop, and APSIM etc. are available and are being frequently used by researchers in India and abroad (Asseng *et al*., 2013; Malone *et al*., 2015; Pandey and Patel, 2012; Singh *et al*., 2010a; Ghosh *et al*., 2014 Vashisth *et al*., 2011).Models provide almost the real picture of experiment, if the input data used in models are actual soil properties, weather condition, typical genotypic behavior of crop and actual management practice employed to grown the crop. DSSAT simulation studies of elevated CO_2 on wheat crop have been reported for reliable responses over others simulation models (Aggarwal and Sinha, 1993; Attri and Rathore, 2003; Ko *et al.*, 2010; Rosenzweig *et al.*, 2014).

Keeping the aforesaid points in view the study entitled "Effect of periodical CO_2 enrichment on wheat *cv.* PBW 343 through Field and Simulation study" has been undertaken with the under mentioned objectives:

1. To assess the effect of periodical CO_2 enrichment on microclimatic change in wheat crop.
2. To evaluate the effect of periodical CO_2 enrichment on growth, development, yield and quality of wheat crop.
3. To calibrate and validate the DSSAT CERES-Wheat model using input data of field experiment.
4. To suggest the agronomic ways and means to improve the productivity of wheat under changing climate.

Chapter-2

REVIEW OF LITERATURE

This chapter is devoted to review the studies relevant to our objectives. Reviews from India and abroad are presented under the following heads:

2.1 Effect of climate change on wheat crop

2.2 Effect of elevated CO_2 on growth and development of Wheat.

2.3 Effect of elevated CO_2 on Yield and Yield attributes of Wheat.

2.4 Effect of elevated CO_2 on quality of Wheat.

2.5 Use of CERES-wheat model in climatic response of wheat.

2.1 Effect of climate change on wheat crop

In the recent years, changes in temperature and rainfall were observed in the global and regional scale. This phenomenon was termed as climate change. These changes in terms of quantity, intensity, duration and time of occurrence cause problems in the agricultural production. Behind these aberrant causes "greenhouse effect" is an at most common phenomenon. The chief cause of the greenhouse effect is an increase in the concentration of GHGs (CO_2, CH_4 and N_2O and CFC) due to anthropogenic activities. They absorb short wave radiation from the sun and re-radiation in the atmosphere that leads to warming. These GHGs trap outgoing infrared from the earth's surface and raise the temperature of the earth and alter the hydrological cycle. In certain places, climatic extremes such as drought and floods have increased. The global mean annual temperature at the end of the 20th Century was increased by 0.5-0.7 ºC as compared to the end of the 19th century. Although the some high latitude northern regions (Europe) of the world may become climatically viable for crop production (Rosenzweig *et al*., 2014; Wheeler and Von Braun, 2013) along with the Mediterranean region (Ludwig and Asseng2006; Ludwig *et al.*, 2009) but tropical and subtropical regions may face severe hot days and dry periods (Cline, 2007; Teixeira *et al*., 2013). Developing countries are more vulnerable to extremes of climatic variation (Thornton *et al*., 2014; UNFCCC, 2007, Ko *et al*., 2014), moreover, the occurrences of drought, heat, cold and flood are now more frequent and intense. As far as the global warming is concerned, it will be uneven, but is expected to be lower on the ocean than land surface (Solomon, 2007). It is clear from some recent findings, that the potential absorption of CO_2 is higher in deep seas due to which ocean surface temperature may increase faster than forecasted from climate models (Balmaseda *et al*., 2013). Risk of flooding on agricultural land in the coastal region is likely to increase with the rise in sea level (Solomon, 2007). Aberrant changes during monsoon period likely to affect the crop production in India (Mukherjee *et al.,* 2014; Niwas and Khichar, 2016).

If the present pace of anthropogenic activities continues in the future, the days are not so far when Indian agriculture will be at a cross road. By 2050 country's population is expected to grow about 1.6 billion that will surpass China, the most populous country in the world. The undisturbed continuous increases in the population will increase the demand for food. If production does not increase in pace with the population, per capita availability of food grain will decrease (Choudhary *et al*., 2014). Researchers have also reported the problem of resource degradation in the country (Bhagat*et al*., 2009), especially in intensive cultivated region *i.e*. Indo-Gangetic Plain (IGP) zone. Long-term experiments conducted at several locations in the IGP have shown a declining trend in productivity (Ladha *et al.,* 2003). The water table in the northern plain zone of India is receding at 0.2 to 0.5 meter per annum, soil salinity and water logging is the other problems that have already spread to several irrigation commands.

2.2 Effect of Elevated CO_2 on Growth and Development of Wheat

A total of 18 research papers with 55 experiments reporting on the effect of elevated CO_2 on growth of wheat from across the world have been reviewed and presented in **Table 2.1**. The CO_2 enrichment increased (significantly and marginally both) the tiller count, plant height (cm), leaf area, leaf weight, stem weight, root weight, earhead weight and plant dry weight of wheat grown in CGC (closed growth chamber), OTC (open top chamber), FACE (free air CO_2 enrichment), GH (glass house), PEC (poly ethylene chamber) and under field condition, without the constraint of moisture, nutrient and temperature but impact was not favorable when grown under stressed condition (Wu *et al*., 2004; Pal *et al*., 2005; Uprety *et al*,. 2009; Masle, 2000; Hogy *et al*., 2009a; Hogy *et al*., 2009b; Hogy *et al*.,2010; Hogy *et al*.,2013; Batts *et al*.,1998; Qiao *et al*.,2010; Li *et al*., 2007; Seneweera *et al*.,2005b; Deepak & Agrawal, 1999; Mishra *et al*.,2013; Wall *et al*.,2006; Benlloch-Gonzalez *et al*.,2014; Zhang *et al*.,2013; Dahal *et al*.,2014). Physiochemical growth parameters such as photosynthesis (μmol m^{-2} sec^{-1}), stomatal conductance (mol m^{-2} sec^{-1}), and total chlorophyll (mgg^{-1} of fresh weight) was reported to increase under elevated CO_2 condition in all the wheat species (*diploid, and hexaploid and tetraploid*). The increment was more prominent in the case of *tetraploid* species

(Pal *et al.,* 2005). Total chlorophyll content was reported to increase up to 20 ºC temperature, whereas, drastically decreasing pattern was noticed when temperature decreases up to 5ºC, it shows that the increasing temperature, due to elevated CO_2 might be improve the chlorophyll content and phenological expressions (Dahal *et al.*, 2014, Pal *et al.,* 2005, Bishnoi *et al.*,1995).

Deepak and Agrawal (1999) conducted an experiment to evaluate the effect of elevated CO_2 and SO_3 alone and in combination on wheat crop and reported that a root/shoot ratio was decreased significantly under elevated CO_2 and under CO_2+SO_2 at 45 DAS whereas no any change was noticed at 60 DAS. LAR tends to increase under elevated CO_2 at 60 DAS but decreases when SO_3 was exposed to CO_2. Similarly RGR, NAR and SLW were increased under CO_2 as well as CO_2+SO_2 treatment and decreases when the plant was exposed under SO_2 alone. The leaf weight ratio was increased under elevated CO_2 at both the stages.

Detailed study on development characters of wheat variety HUW-37 and K-9107 was carried out by Mishra *et al.,* (2013) under elevated CO_2 and elevated O_3 condition and reported that under elevated O_3 NAR was significantly reduced by 35.8 and 29.8%, whereas it was increased under elevated CO_2 by 24% and 30%, respectively in comparison to the ambient condition at 40–60 DAG. LAR significantly increased by 48.7 and 35.1% under elevated CO_2 and reduced under elevated O_3 by 16.8 and 18.6%, respectively for both the cultivars at 60 DAS. Similarly SLW tends to reduce by 30% and 22% under elevated O_3 whereas, significantly increased under elevated CO_2 at 60 DAS. SLA was also increased by 44 and 29%, respectively under elevated CO_2 at 60 DAS. LWR was also increased significantly by 42.8 and 27.6% under elevated CO_2, while the change was insignificant under elevated O_3 at 60 DAS. Root/Shoot ratio was significantly increased by 26.3 and 57% under elevated CO_2 condition.

High yielding varieties with larger plant canopy are more benefited under elevated CO_2 in comparison to shorter canopy (Hasegawa *et al.,* 2013), indicates that the response of the elevated CO_2 is as greater as the sink size of the plant.

Table 2.1: Effect of elevated CO_2 on growth and development of wheat

S. No.		CO_2 level (ppm)	Other factor	% Change in growth and development								Exp. site	Cultivar	Technique used	Scientist reported
				Tiller	Height	Leaf area	Leaf weight	Stem weight	Root weight	Earhead weight	Plant weight				
1	a	350, 700	Irrig. at 80 % FC	-	56	-	-	-	-	-	E= 30.7, B= 86.0, GF= 133.1, H= 89	Lanzhou, China	SW (*T. aestivum*) *cv*. Ganmai 8139	CGC	Wu*et al.*,2004
1	b	350, 700	Irrig. at 40 % FC	-	27	-	-	-	-	-	E=8.8, B=8.4, GF=52.7, H=53.1	Lanzhou, China	SW (*T. aestivum*) *cv*. Ganmai 8139	CGC	Wu*et al.*,2004
2	a	300, 600	N_{75},40DAS	-	40.2	29.7	- 6.1	103.4	88.9	-	100.0	IARI, India	WW (*T. aestivum*) *cv*. HD-2285	OTC	Pal*et al.*,2005
2	b	300, 600	N_{150},40DAS	-	53.1	45	-14.7	117.5	90.0	-	113.4	IARI, India	WW (*T. aestivum*) *cv*. HD-2285	OTC	Pal*et al.*,2005
2	c	300, 600	N_{75}, 60DAS	-	35.9	44.8	12.0	126.5	131.6	-	127.5	IARI, India	WW (*T. aestivum*) *cv*. HD-2285	OTC	Pal*et al.*,2005
2	d	300, 600	N_{150},60DAS	-	49.8	38.4	59.6	143.9	147.6	-	144.9	IARI, India	WW (*T. aestivum*) *cv*. HD-2285	OTC	Pal*et al.*,2005
2	e	300, 600	N_{75}, 90DAS	-	14.3	22.8	-1.0	87.6	129.4	-	91.6	IARI, India	WW (*T. aestivum*) *cv*. HD-2285	OTC	Pal*et al.*,2005
2	f	300, 600	N_{150},90DAS	-	15.4	38	3.7	96.0	122.4	-	103.2	IARI, India	WW (*T. aestivum*) *cv*. HD-2285	OTC	Pal*et al.*,2005
3	a	375, 550	Diploid	-	-	8.03	7.9 (P)	-33.4*	-16.7**	-	7.44	IARI, India	WW *(T. monococcum) cv*.PBW-373	FACE	Uprety *et al., 2009*
3	b	375, 550	Tetraploid	-	-	18.49	19.3 (P)	-37.1*	-21.8**	-	4.80	IARI, India	WW *(T. durum) cv*. PBW-373	FACE	Uprety *et al., 2009*
3	c	375, 550	Hexaploid	-	-	8.03	6.9 (P)	7.23*	1.7**	-	7.44	IARI, India	WW *(T.aestivum) cv*. PBW-373	FACE	Uprety *et al., 2009*
4	a	350,	Ele.CO_2+	-	-	82.2	-	-	-	-	93.2	Canberra	WW	GH	Masle,

S. No.		CO_2 level (ppm)	Other factor	% Change in growth and development								Exp. site	Cultivar	Technique used	Scientist reported
				Tiller	Height	Leaf area	Leaf weight	Stem weight	Root weight	Earhead weight	Plant weight				
		900	Vern.									Australia	(*T.aestivum*) *cv.* Hartog and *cv.* Birch 75		2000
	b		Ele. CO_2	-	-	80	-	-	-	-	91.1				
	c		Ele. CO_2+ Vern.	-	-	57.1	-	-	-	-	80.1				
	d		Ele. CO_2	-	-	38	-	-	-	-	52.3				
5	-	375, 525	Ambient Elevated	-	-	-	-1.2	10.4	-	17.2	11.8	Stuttgart Germany	SW *(T. aestivum) cv.* Triso	Mini-FACE	Hogy *et al.*,2009a
6	-	375, 525	Ambient Elevated	-	-	-	13.5	26.3	-	13.3	18.8	Stuttgart Germany	SW (*T.aestivum*) *cv.* Triso	Mini-FACE	Hogy*et al.*,2009b
7	-	409, 537	Ambient Elevated	-	-	-	-8.5	14.9	-	10.9	10.4	Stuttgart Germany	SW (*T.aestivum*) *cv.* Triso	Mini-FACE	Hogy*et al.*,2010
8	-	375, 526	Ambient Elevated	-	-	-	5.1	7.6		9.6	8.5	Stuttgart Germany	SW (*T.aestivum*) *cv.* Triso	Mini-FACE	Hogy*et al.*,2013
9	a	370, 700	+1.0°C	-	-	-	-	-	-	-	↑ ns	Reading (UK)	WW (*T. aestivum*) *cv.* Hereward	Polyethylene chamber	Batts*et al.*,1998
	b		+1.8°C	-	-	-	-	-	-	-	77.3				
	c		+2.0 °C	-	-	-	-	-	-	-	68.5				
	d		+1.2 °C	-	-	-	-	-	-	-	87.4				
10	a	353, 712	Irrigated	-	0.9	-	-	-	-	-	6.45	Luancheng, China	WW (*T. aestivum*) *cv.* Kenong 9204	OTC	Qiao*et al.*,2010
	b		Unirrigated	-	1.5	-	-	-	-	-	13.55				
11	a		CK (Control)	$0.0^{\#}$	$0.0^{\#\#}$	$0.0^{\#\#\#}$	-	-	-	-	-	Dingxi,	SW (*T.*	Under Field	Li *et al.*,

S. No.		CO_2 level (ppm)	Other factor	% Change in growth and development								Exp. site	Cultivar	Technique used	Scientist reported
				Tiller	Height	Leaf area	Leaf weight	Stem weight	Root weight	Earhead weight	Plant weight				
	b		C	2.4[#]	7.9[##]	10.9[###]	-	-	-	-	-	China	*aestivum)* *cv.* 'Dingxi 24	Situation	2007
	c		W	1.2[#]	35.0[##]	25.5[###]	-	-	-	-	-				
	d		W+C	8.9[#]	56.6[##]	36. 5[###]	-	-	-	-	-				
	e		W+N_1	15.4[#]	42.5[##]	42.7[###]	-	-	-	-	-				
	f		W+N_2	17.2[#]	50.9[##]	48.4[###]	-	-	-	-	-				
	g		W+N_1+C	21.9[#]	64.9[##]	53.1[###]	-	-	-	-	-				
	h		W+N_2+C	26.0[#]	70.6[##]	59.4[###]	-	-	-	-	-				
12	-	370, 700	-	-	-	32.1	-	-	-	-	36.4	Sendai Japan	WW (*T. aestivum)cv.* Hartog	GC	Seneweera *et al.*,2005b
13	a	350, 600 at 40 DAS	CO_2 (350 ppm)	19.7	18.02	33.6	32.9	61.9	-	-	-	Varanasi India	WW (*T. aestivum)cv.* Malviya 234	OTC	Deepak and Agrawal, 1999
	b		SO_2 (0.06 ppm)	6	8.2	13.8	20.5	9.5	-	-	-				
	c		CO_2+SO_2 (350 + 0.06 ppm)	22.38	20.2	39.6	49.3	80.9	-	-	-				
	a	350, 600 at 60 DAS	CO_2 (600 ppm)	14.7	13	38.2	36.5	65.9	-	18.7	-				
	b		SO_2 (0.06 ppm)	-10.0	-9.0	-14.8	-8.9	-9.8	-	6.25	-				
	c		CO_2+SO_2 (600 + 0.06 ppm)	17	16.1	29.5	30.3	85.4	-	12.5	-				
14	a	388, 548	A	-	0	0	0	0	-	-	-	Varanasi, India	WW (*T. aestivum)cv.* HUW-37 and *cv.* K-9108	OTC	Mishra *et al.*,2013
	b		B[1]	-	↑	↑	↑	↑	-	-	-				
	c		C[1]	-	↓	↓	↓	↓	-	-	-				
	d		D	-	↑	↑	↑NS	↑NS	-	-	-				
15	a	363,	Irrigated	-	-	-	63	18	-	-	-	Maricopa,	SW (*T.*	FACE	Wall *et*

S. No.		CO_2 level (ppm)	Other factor	% Change in growth and development								Exp. site	Cultivar	Technique used	Scientist reported
				Tiller	Height	Leaf area	Leaf weight	Stem weight	Root weight	Earhead weight	Plant weight				
	b	548	Unirrigated	-	-	-	17	22	-	-	-	USA	*aestivum)cv*. YecoraRojo		*al.*,2006
16	a	380, 700	High vigor	-	-	-	0	-	0	-	0	Córdoba, Spain	SW (*T. aestivum)cv*.CV - 97, 207	GH	Benlloch-Gonzalez *et al.*,2014
	b		Low vigour	-	-	-	97	-	67	-	43				
17	a	400, 760	0 Kg Nha^{-1}	-	8.1	3.1	-	-	-	-	-	Gansu, China	SW (*T. aestivum)*	OTC	Zhang *et al.,* 2013
	b		200 Kg Nha^{-1}	-	1.9	2.4	-	-	-	-	-				
18	a	380, 700	20 ˚C	-	-	-	13.3	-	20.1	-	27.6	Ontario, Canada	WW (*T. aestivum)cv.* Norstar	GC	Dahal *et al.*,2014
	b		5 ˚C	-	-	-	6.9	-	-3.3	-	33.2				
	c		20 ˚C	-	-	-	11.1	-	14.5	-	39.2		SW (*T. aestivum)* *cv.* Katepwa		
	d		5 ˚C	-	-	-	16.7	-	-19.8	-	12.5				

Where,

E=Elongation; B= Booting; GF= Grain filling; H= Harvest stages; P= Photosynthesis (µmol m^{-2} sec^{-1}); *SC= Stomatal conductance (mol m^{-2} sec^{-1}); **TC= Total chlorophyll (mg g^{-1} fresh wt); #LAI-J= Jointing; ##LAI-F= Flowering; ###LAI-GF= Grain filling; A = Ambient CO_2 (388.4 ±37.3) and O_3 (48.4±4.6); B^1= CO_2 (548.2 ±53.7) and O_3 (48.4±4.6); C^1= CO_2 (388.4 ±37.3) and O_3 (55.2±5.3); D= CO_2 (548.2 ±53.7) and O3 (55.2±5.3); ↑= Significant increase as compare to control (0) at 40, 60 and 80 days after germination (DAG); ↓= Significant decrease as compare to control (0) at 40, 60 and 80 DAG, ns indicates non-significant change; W= With 90 mm irrigation-three times but without applications of CO_2 forming fertilizer and CO_2 gas; WC= W+ artificial application of CO_2 gas (40 mmol mol^{-1}) but without CO_2 forming fertilizer application; WN_1= W+fertilizer application (NH4NO3: 250 kg ha^{-1}) but without CO_2 gas applications; WN_2= W+fertilizer application (NH4HCO3: 500 kg ha^{-1}) but without CO_2 gas applications; WN_1C= WC+WN_1; WN_2C= WC+WN_2; C= CO_2 40 mmol mol^{-1} but without irrigation and CO_2 forming fertilization; CK=Without irrigation, fertilization and CO_2 gas application; OTC= Open top Chamber; WW= Winter Wheat; SW=Spring Wheat, CGC= Closed growth chambers; OTC= Open top chambers; GH= Green house; GC= Growth Chambers; SW= Spring wheat; WW= Winter wheat.

2.3 Effect of Elevated CO_2 on Yield and Yield Attributes of Wheat

Some of the factors directly associated with the yield of a crop such as- total number of plants per unit area, effective tillers or panicles per plant, grain per ear head, grain weight, test weight *etc*. More or less all these yield components are affected by the accumulation of photosynthates under a given treatment. The response of elevated CO_2 on these characters in wheat has now become an established fact.

The summary (Dubey *et al,* 2015a) of eleven studies with 28 experiments presented in **Table 2.2** recorded increased grain yield, biomass yield, number of ear plant^{-1}, grain number ear^{-1}, grain number m^{-2}, thousand grain weight (TGW) and Harvest Index (HI) in response to CO_2 application in wheat (Deepak and Agrawal, 1999; Batts *et al.,* 1998; Uprety *et al.,* 2009; Högy *et al.,* 2009a, Högy *et al.,* 2009b, and Hogy *et al.,* 2010a; Xiao*et al.,*2009; Li*et al.,* 2007; Qiao*et al.,* 2010; Bencze *et al*., 2004; Dijkstra *et al.,* 1999; Rai *et al.,* 2016; Abebe *et al.,* 2016; Satapathy *et al*., 2015 and Cai *et al.,* 2015).

Alabebe *et., al* (2016) conducted an experiment on wheat in India under open top chambers (OTCs) to determine the effects of elevated atmospheric carbon dioxide (CO_2) and temperature on growth, yield and yield attributes of wheat and reported that elevated CO_2 increased grain yield of wheat by 21.36 % with greater grain number and harvest index (HI) by 6.56% compared to ambient CO_2 whereas, elevated temperature by 1.5°C and 3.0°C decreased grain yield by 9.39% and 18.18%, respectively. Simultaneous elevation of CO_2 and temperature increased number of tiller m^{-2}, number of spike m^{-2}, straw yield, biological yield but decreased days to 50% anthesis, plant height, number of grains spike^{-1} and grain weight spike^{-1}.

Cai, *et al*., (2016) conducted an experiment on wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) under two levels of CO_2 (ambient and enriched up to 500 μmol mol^{-1}) and two levels of canopy temperature (ambient and increased by 1.5–2.0 °C) in free-air CO_2 enrichment (FACE). Result revealed that the elevated CO_2 enhances the grain yield and several yield contributing characters, whereas elevated temperature reduced, in both the crops. Elevated CO_2 was not able to compensate the negative impact of temperature on biomass and yield of wheat and rice. Yields of wheat and rice were decreased by 10–12% and 17–35%, respectively, under the combination of elevated CO_2 and temperature.

Table 2.2: Effect of elevated CO_2 on yield and yield attributes of wheat

S.No		CO_2 Level (ppm)	Other factor	% Change in yield and yield attributes							Experimental site	Cultivar used	Experimental condition	Scientist reported
				Grain yield	Biomass yield	Earheads per plant	Grain per earhead	Grain m^{-2}	1000 Grain wt	Harvest index				
1	a	350, 700	80 % of FC	166	-	-	140	-	-	30	Lanzhou, China	SW (*T. aestivum*) *cv*. Ganmai 8139	CGC	Wu*et al.*, 2004
	b		40% of FC	78	-	-	42	-	-	41.9				
2	a	375; 550	Diploid	13.25	21.37	-	-	-	5.33	5.41	IARI, India	*T. monococcum cv* PBW-373	FACE	Uprety *et al.*,2009
	b		Tetraploid	15.9	25.9	-	-	-	-10.04	10.58		*T. durum cv* PBW-373	FACE	
	c		Hexaploid	13.25	21.37	-	-	-	5.33	5.41		*T. aestivum cv*. PBW-373	FACE	
3	a	380, 410	CO2	5.1		0.1	2.5		12.5	1.3	Guyuan, China	SW (*T. aestivum*) *cv*. AD-2)	OTC	Xiao*et al.*, 2009
	b		CO2+ NH4 CO3	82		-0.2	15.6		51.7	11.9				
4	-	375, 525	-	23.08	11.8	6.9	7.22	12.2	-1.7	-	Stuttgart, Germany	SW (*T. aestivum*) *cv*. TRISO	Mini-FACE	Högy *et al.*, 2009a
5	-	375, 525	-	13.5	18.8	22.4	-4.9	14.8	-1.9	-5.3	Stuttgart, Germany	SW (*T. aestivum*) *cv*. TRISO	FACE	Högy *et al.*, 2009b
6	-	409, 537	-	10.7	10.4	-	12.2	12	-0.3	0.5	Stuttgart, Germany	SW (*T. aestivum*) *cv*. TRISO	Mini- FACE	Hogy *et al.*, 2010
7	-	Ambient, +150	-	10.8	-	4.7	0.5	5.2	5.4	2.2	Stuttgart, Germany	SW (*T. aestivum*) *cv*. TRISO	Mini-FACE	Högy *et al.*, 2013
8	a	370, 700	+1.0°C	7-44 ↑	6-31 ↑	-	82.5	-	-	-	Reading (UK)	W.W (*T. aestivum*) *cv*. Hereward	Polyethylene chamber	Batts *et al.*,1998
	b		+1.8°C	21-56 ↑	34 ↑	-	71.5	82.8	-	-				
	c		+2.0 °C	46-57 ↓	8-17 ↑	-	46.4	78.4	-	-				
	d		+1.2 °C	31-58 ↓	33-17 ↓	-	15.8	-	-	-				

S.No		CO_2 Level (ppm)	Other factor	% Change in yield and yield attributes							Experimental site	Cultivar used	Experimental condition	Scientist reported
				Grain yield	**Biomass yield**	**Earheads per plant**	**Grain per earhead**	**Grain m^{-2}**	**1000 Grain wt**	**Harvest index**				
9	a	353; 712	Irrigated	6.5	-	8.7	8.6	-	-2.42	-	Luancheng, China	WW (*T. aestivum*) *cv.* Kenong 9204	OTC	Qiao*et al.*, 2010
	b		Un irrigated	10.43	-	17.11	-2.8	-	-1.39	-				
10	a	CO_2 forming fertilizer	CK(Control)	0	0	0	-	-	0	0	Dingxi China	SW *(T. aestivum)cv* . 'Dingxi 24	Under Field Situation	Li *et al.*,2007
	b		C	4.2#	4##	1.5###	-	-	-0.3	0.2				
	c		W	73.4#	47.3##	7.5###	-	-	-0.6	-0.6				
	d		W+C	90.4#	49.5##	13.4###	-	-	1.1	0.9				
	e		W+N_1	148#	51.9#	35.8###	-	-	3	4.7				
	f		W+N_2	163.6#	63.4##	62.7###	-	-	3.3	3.9				
	g		W+N_1+C	180.5#	66.7##	97###	-	-	5.2	5.6				
	h		W+N_2+C	197.1#	72.3##	100###	-	-	5.8	6.7				
11	a	350; 600	CO_2 (600 ppm)	30.5	-	35.13	1.22	35.71	3.86	16.22	Varanasi India	W.W *(T. aestivum)* *cv.* Malviya 234	OTC	Deepak and Agrawal, 1999
	b		SO_2 (0.06 ppm)	-15.4	-	-27.02	1.84	-19	4.45	-4.67				
	c		CO_2+SO_2 (600+0.06) ppm)	41.8	-	56.75	2.45	40.28	0.99	18.71				

Where,

FC =Field capacity; #LAI-J= Jointing; ##LAI-F= Flowering; ###LAI-GF= Grain filling; ↓= Significant decrease as compare to control (0); ns = non-significant change; C= CO_2 40 mmol mol^{-1} but without irrigation and CO_2 forming fertilization; CK=Without irrigation, fertilization and CO_2 gas application; W= With 90 mm irrigation-three times but without applications of CO_2 forming fertilizer and CO_2 gas; WC= W+ artificial application of CO_2 gas (40 mmol mol^{-1}) but without CO_2 forming fertilizer application; WN_1= W+fertilizer application (NH4NO3: 250 kg ha^{-1}) but without CO_2 gas applications; WN_2= W+fertilizer application (NH4HCO3: 500 kg ha^{-1}) but without CO_2 gas applications; WN_1C= WC+WN_1; WN_2C= WC+WN_2; OTC= Open top Chamber; WW= Winter Wheat; SW=Spring Wheat, CGC= Closed growth chambers; OTC= Open top chambers; GH= Green house; GC= Growth Chambers; SW= Spring wheat; WW= Winter wheat.

2.4 Effect of Elevated CO_2 on Quality of Wheat

In general, under elevated CO_2 plant typically accumulate more C in comparison to other elements, thus the concentration of another element, such as N, P, K and traces elements start decreasing concomitantly in plant tissues (Cotrufo *et al.*, 1998; Gifford *et al.,* 2000) whereas the concentration of carbon-rich molecules (carbohydrate) starts increasing (Poorter *et al.,* 1997). Another element (N, P, K, Ca, Mg, and S) based molecules such as protein; amino acid etc. tends to decrease as CO_2 increases. Loladze, (2002) conducted a meta-analysis and contended that 'globally imbalanced plant stoichiometry' may be led by elevated CO_2 if the current trend of CO_2 is continue, it will negatively influenced the human nutrition, especially in case of most important micronutrients *i.e.* zinc and iodine. Experiment on six major food grains was carried out under elevated CO_2 by Dietterich *et al.,* (2015) and reported the detrimental effect on various quality components. Idso and Idso, (2001) reviewed the number of studies related to the elevated CO_2 impact on food compositions of various crops and observed that the researchers are not unanimous for any particular nutrients in any crop. Even after several researches the relative effects of elevated CO_2 on grain protein under various environmental conditions was not clear (Fernando *et al.*, 2014a). Detailed impact of elevated CO_2 on various quality components are given below.

2.4.1 Protein

Taub *et al*., (2008) conducted a meta-analysis to know the impact of elevated CO_2 on the protein concentration of 'wheat grain' and 'wheat flour' using 87 and 28 observations, respectively, and noticed that the decrease in protein concentration under elevated CO_2 was 11 % in grain and 6 % in flour respectively. Hogy *et al*., (2008) conducted a brief review to know the impact of elevated CO_2 on wheat in respect to growing environments; (i) small pots <10 liter rooting volume capacity; (ii) Larger pots < 10 rooting volume capacity, and CO_2 exposure techniques (open field, the laboratory growth chamber (GC), glasshouse/greenhouse (GH), closed (or closed-top) field chamber (CTC) and under open-top field chamber (OTC)). It was observed that under small rooting volume pots the protein concentrations decreased by 1.4, 4.0, and 14.1 percent in GC, GH and OTC, respectively due to elevated CO_2; in large rooting volume pot under GC and OTC, concentration was decreased by 8.1 and 6.4 percent, respectively, overall decrease in concentration was 4.2, 3.9 and 2.3 percent in CTC, OTC and FACE, respectively. Hogy *et al.,* (2009b) conducted an experiment on wheat under FACE with ambient and elevated CO_2 (526 ppm) and reported the significant decrease (3.5%) in total grain protein concentration under elevated CO_2 however, total protein yield (gm^{-2}) was increased by 9.5%. Blumenthal *et al.,* (1996) conducted a study on wheat crop in the field under controlled-atmosphere tunnels with ambient (350 ppm) and elevated CO_2 level and noticed the decreased protein concentration (8.7%) in wheat flour under elevated CO_2. Fernando *et al.,* (2012) used Australian grains free-air carbon dioxide enrichment (AGFACE) to test the wheat crop under current (384 ppm) and elevated CO_2 (550 ppm) with two different sowing times and reported that the grain protein was decreased by 12.7% under elevated CO_2; the reduction was highest under late sown crop. Hogy *et al.*, (2013) evaluated the effect of elevated CO_2 under the FACE system in Germany and reported the decreased protein concentration by 7.9 percent under CO_2 enrichment. Chemical composition and nutritional value of winter wheat and barley grown at two CO_2 levels (ambient CO_2 and elevated 550 ppm), with two nitrogen levels (adequate N-100 and 50% of adequate N-50 was evaluated by Wroblewitz *et al.*, (2013) and observed that the crude protein declined significantly under elevated CO_2 condition from 8-16 g per kg and 10-20 gper kg in wheat and barley.

Kimball *et al*., (2001) conducted two FACE experiments (550 ppm) in adequate (wet) and poor irrigated (dry) condition, along with two nitrogen concentrations (High-N and Low-N) by using wheat as test crop. The result revealed that the protein content and loaf volume was increased by 2 and 3 %, respectively under dry situation in comparison to wet. Under low N condition protein content and loaf volume was decreased by 36 % and 26 %, respectively. Whereas, at ample water and High-N condition protein and loaf volume was slightly decreased by 5 % and 2 %, respectively. Piikki *et al.,* (2008) evaluated the effects of O_3 and CO_2 on the quality of spring wheat using 13 European OTC experiments dataset conducted in three countries in 10 years on four wheat cultivars. The study revealed that the protein yield was significantly reduced because of the reduction in 1000-grain weight when the plant was exposed under O_3 though the total grain protein and its component (Zeleny value and the Hagberg falling number) was significantly increased. Hogy *et al.* (2008) also noticed the decreased concentration of total gluten (dry and wet gluten) under elevated CO_2. Under OTC, elevated CO_2 cause significant decrease in dry and wet gluten by 7.1% and 7.5 %, respectively, wet gluten concentration was slightly reduced by 3.0 in a glass chamber. Insignificant decrease was noticed in Green House exposure, although the concentration was decreased by 6.3% after season long CO_2 fumigation. Bencze *et al.,* (2004) reported the negative impact of elevated CO_2 and high temperature on the protein and gluten contents, lowest gluten index was observed in combination of both CO_2 and high temperature. Fangmeier *et al.,* (1999) observed the significant decrease in various gluten parameters, *i.e.* dry/wet gluten content, Zeleny value, Hagberg value when CO_2 concentration increased from 360 to 680 ppm. Reduction in total gliadins was reported by Hogy *et al.*, (2013) under CO_2 enrichment condition, gluten content (both gliadins and glutenins) was decreased by 11.3%, whereas albumins/globulins and total glutenins were unchanged. Mishra *et al.,* (2013) reported the significant decrease in grain protein content by 8.9 and 5.4% under elevated CO_2 and 18.8 and 15.3% under O_3 for wheat variety HUW-37 and K-9107, respectively.

2.4.2 Amino Acids

Elevated CO_2 tends to reduce the concentrations of total amino acids after hydrolysis in wheat grains by 6.1-23.9% in OTCs, except for Prolien (which increased by 1.0%, but the change was non-significant) reviewed by Hogy *et al.,* (2008). Furthermore, the concentrations of amino acids were reduced between 0.2 and 8.3%, except serine, though the effects were only significant for Glycine and Valine (Hogy *et al.* 2009a). Under elevated CO_2 glutamine and Proline was significantly decreased by 10.7% and 9.7%, (Hogy *et al.* 2009b). All proteinogenic amino acids were reduced by 4.2 to 7.9% per unit flour mass under elevated CO_2 in wheat crop (Hogy *et al.* 2013). Mishra *et al.* (2013) noticed the significant reductions in total free amino acids by 10.4 and 6.9% under elevated CO_2 and by 20.2 % and 17.4% under elevated O_3 for wheat cultivar HUW-37 and K-9107, respectively grown at Varanasi Uttar Pradesh, India.

2.4.3 Carbohydrate

The increases in starch content were noticed by 5.2, 2.7 and 4.4% in GC, GH and OTC under larger pots (Hogy *et al.* 2008). Total non-structural carbohydrates and starch concentrations decreased, whereas fructose, raffinose and fructan increases under CO_2 enrichment (Hogy *et al.,* 2013). Test weight and grain starch content decreases from 55±5 mg to 18±2 mg and from 31±3 mg to 7±2 mg, respectively with increase in temperature, whereas total amylose and lipid-free amylose content increased from 26±1% to 31±1%, and from 21±1% to 25±1%, respectively, with temperature (Tester *et al*., 1995). Significant increase in total soluble sugars by 18.6 and 28.9% under elevated CO_2 and by 9.7 and 13.9% under elevated O_3+ CO_2 for HUW-37 and K-9107, respectively, and starch content by 19.7 and 8.3%, respectively was noticed by Mishra *et al.,* (2013).

2.4.4 Element Nutrients

Fangmeier *et al.,* (1997) conducted a study in OTC to test the impact of elevated CO_2 on wheat in combination with O_3 under various nitrogen levels and observed that the elevated CO_2

improved the NUE by lowering the demand of nitrogen in green tissues, grain N concentration along with Ca, S, Mg and Zn were tending to decrease under CO_2 enrichment whereas, P concentration was unaffected. In case of biomass, concentration of K, Mn, P, Mg increased N, S, Fe, Zn were unaffected and Ca was decreased under CO_2 enrichment. Fangmeier *et al.,* (1999) observed again that the grain N concentration decreased by nearly 15% when CO_2 concentrations was doubled from 360 to 680 ppm. Hogy *et al.,*(2008) observed the decreasing response of macro elements (N, Ca, Mg and S) 0.7-19.5% while, K and P were increased by 3.9 and 1.1%, respectively under OTC, whereas under glass chamber K and P,Na, Ca, Mg and S content were significantly decreased by 12.4, 19.5, 5.5, 14.5, 7.2 and 12.3%, respectively. Fernando *et al.,* (2012) observed the significant decrease in concentration of grain S, Ca, Fe and Zn under elevated CO_2 in early sown wheat crop whereas, in late sown crop the concentrations were significantly increased. Pleijel *et al.* (2009) reported the strong correlation in grain protein and Zn concentration (R^2 = 0.90) thus the rising CO_2 concentrations are likely to reduce Zn concentrations of wheat grain by reducing the protein content. Thompson & Cohen (2015) examined the report from 188 countries and observed that the elevated CO_2 lowered the zinc and other nutrients in major crop which may cause endemic diseases, the population are at higher risk those depend on staple crops for their food requirement. Myers *et al.,* (2015) reported that the South Asian and sub-saharan region is more prone to zinc deficiency because their most of the dietary requirement met by staple crop.

2.5 Use of CERES-Wheat Model in Climatic Response of Wheat

Under some circumstances, it is really difficult or some time impossible to test the response of crop or variety under certain climatic situation. In that condition, crop simulation models are proven tool to extrapolate the similar behavior as per the user's interest (Ahuja *et al*., 2014; Holzworth *et al*., 2014). Models are the best option to answer "what if". Numerous researchers had employed the crop simulation model under the variety of climatic situations and management options (Ma *et al*., 2016; Vashisth *et al*., 2014; Rana *et al.* 2013; Dass *et al*., 2012; Islam *et al*., 2012; Brassard and Singh, 2008; Brown and Rosenberg, 1999).The model can provide better transparency of alternative approaches (Holzworth et al. 2015).Various models are frequently being used in agriculture to simulate the number of options (Ewert *et al.* 2002; Deryng *et al*., 2014; O'Leary *et al*., 2015). White *et al.* (2011) carried out a critical review of simulation study by analyzing 221 peer-reviewed research conducted across the world and observed that over more than 30% cases CERES series model has been used. These models are most robust model developed by scientists associated with the International Consortium for

Agricultural Systems Applications (ICASA), frequently being used for the wide range of climate over the globe (Lal *et al.,* 1998; Cuculeanu *et al.,* 1999; Alexandrov and Hoogenboom 2000; Shi *et al.,* 2001; Tubiello *et al.,* 2002; Singh *et al.,* 2010b). In India, DSSAT is one of the proven model to simulate the crop yield under wide range of management options. India Meteorology Department recommended this model and frequently use to predict the yield of major crops at district level in the country. It is a process oriented Cropping System Model (CSM) that has the capability to simulate the growth, development, biomass production of crops over the time as well as the soil water, carbon and nitrogen processes and management practices under dynamic environmental situation (Hoogenboom *et al*., 2004;). To evaluate the impact of elevated CO_2 on wheat crop this model was frequently used by various researchers (Vashisth *et al*., 2015; Singh *et al*., 2016; Sudhishri and Dass, 2006).

Over the world numerous simulation models were tested along with experimental studies. Ewert *et al.,* (2002) tested three crop simulation models (LINTULCC2, AFRCWHEAT2, and Sirius) to evaluate the effect of elevated CO_2 and drought on wheat grown in the FACE (open field) and OTC. Deryng *et al*., (2014) studied the response of maize, spring wheat and soybean yields using global crop model PEGASUS to evaluate the impacts of temperature stress and climate change during the 21st century and proposed that the yield of spring wheat and soybean may be improve globally by 2080s (except the tropics and sub-tropics regions)due to elevated CO_2. O'Leary *et al*., (2015) conducted wheat crop experiments to know the response of elevated CO_2 under Australian AG-FACE in Australia. For this purpose six models *i.e.* APSIM-Wheat, APSIM-N wheat, CAT-Wheat, CROPSYST, OLEARY-CONNOR and SALUS were tested using actual experimental data and noticed the similar to the experimental result under elevated CO_2. Liu *et al* (2016) tested four wheat models (DSSAT-CERES-wheat, DSSAT-Nwheat, APSIM-Wheat, and Wheat Grow) with 4 years experimental datasets of two cultivars and reported that the grain filling duration may reduce by 30–60% by each increase in heat degree days over 30 °C. Besides these, numerous studies conducted under FACE and validated using crop models (Saseendran *et al.,* 2004; Ko *et al*., 2010; Ludwig and Asseng, 2006; Liu *et al*., 2011; Saseendran *et al.,* 2013; Ma *et al*., 2016).

Various researchers had tested the simulation models to know the response of crops in future climate change scenarios. Estes *et al*., (2013) combined the mechanistic and empirical models to predict the change in crop production specially maize and wheat in future (2055) using 18 downscaled climate scenarios and observed that the average change in maize and wheat yield was -3.6% and 6.2%, respectively in empirical model, whereas 6.5% and 15.2% in the mechanistic model. Deryng *et al*., (2016) combines the results from field experiments and crop models to depict the clear global perspective at regional level on crop water productivity for wheat, maize, rice and soybean crop under elevated CO_2 situation and reported that elevated CO_2 may increase the global crop water productivity by 10 %-27% by the 2080s depending on crop types, highest increase is likely to occur in arid regions (48%) for the wheat crop. To observe the extent of uncertainties in wheat yields under climate change scenario Asseng *et al.,* (2013) uses 27 wheat crop simulation models with field experiments, data for four different environments and reported that the uncertainties in simulated impacts increased with elevated CO_2 concentrations and its associated warming. Attavanich and McCarl (2014) had employed econometric model to observe the impact of elevated CO_2 on various crops and reported that the elevated CO_2 didn't going to affect the production of C_4 crop in the near future, though C_3 crops may be affected positively up to a greater extent.

Impact of elevated CO_2 and climate change on wheat crop in Indian condition is simulated by various researches on various scales. A study carried out by Attri *et al,* (2011) using DSSAT v4.5 model revealed that due to elevated CO_2 reduces the anthesis and maturity period by 2-14% and 2-10%, respectively whereas grain number and yield increases by 4-27% and 6-26%. Kumar *et al*., (2014) observed that the extent of change in DSSAT simulated and actual yield was quite less under Tarai belt of Uttarakhand. Simulation study revealed that the wheat yield of Gujarat may reduce by 8 to 31 % due to elevated temperature and increase by 21 to 68% due to elevated CO_2 (Pandey *et al*. 2009). Tripathi *et al*. (2014) observed that the regression model simulated wheat yield was at par with actual yield of south western Uttarakhand. impact of changing climate on six major wheat varieties grown in the Uttarakhand region of India was tested by Dubey *et al*., (2014) using DSSAT CERES-Wheat model under four hypothetical CO_2 (+100, +200, +300, and +400 ppm from ambient) and temperature (+0.5 $^{\circ}$C, +1°C, +1.5°C and +2°C from ambient) condition and observed that the elevated CO_2 positively affect the grain and biomass yield for entire cultivars whereas temperature reduces significantly. Wheat varieties such as PBW 343, HUW 234 and Raj 3765 are best performer for this region under climate change situation.

Chapter-3

MATERIAL AND METHODS

This chapter describes the methods and material used to carry out the field experiment entitled "Effect of periodical CO_2 enrichment on wheat *cv.* PBW 343 through Field and Simulation study"during *Rabi* season 2011-12 and 2012-13 and the observations recorded.

3.1 Field Experiment

3.1.1 Site description

The field experiment was conducted at the research farm of Department of Water Resource Development and Management, Indian Institute of Technology Roorkee-Haridwar (Uttarakhand) located at 29^0 50' 7'' N latitude, 77^0 55' 18'' E longitude and 262 m altitude above the mean sea level during *Rabi* season (November-April) 2011-12 and 2012-13.

3.1.2 Weather data Collection

Daily weather data of Rainfall (mm), Maximum Temperature (°C), Minimum Temperature (°C), solar radiation (MJ M^{-2} day^{-1}) during the experimental period was recorded from the Automated Weather Station installed in the Agrometeorology Laboratory located at the research farm of Indian Institute of Technology Roorkee. Weather condition during crop growing period are presented in Figure. 3.1.

3.1.3 Soil sampling and analysis

Soil samples from different parts of the experimental field were collected from the depths of 0-15 cm, 15-30 cm, 30- 60 cm, 60-90 cm and 90-120 cm with the help of a 2 meter long soil auger before the start of the crop season. Composite soil sample was prepared separately for each layer. Each sample was air & oven dried, powdered and passed through 2 mm sieve. These samples were stored for the physical and chemical analysis of soil.

Sand (<0.02 mm) and silt (0.02-0.002 mm) content was analyzed by hydrometer method (Bouyoucos, 1962). Bulk density (BD) was estimated by core method. Field Capacity (FC) and Permanent Wilting Point (PWP) were estimated using pressure plate apparatus. Soil color was

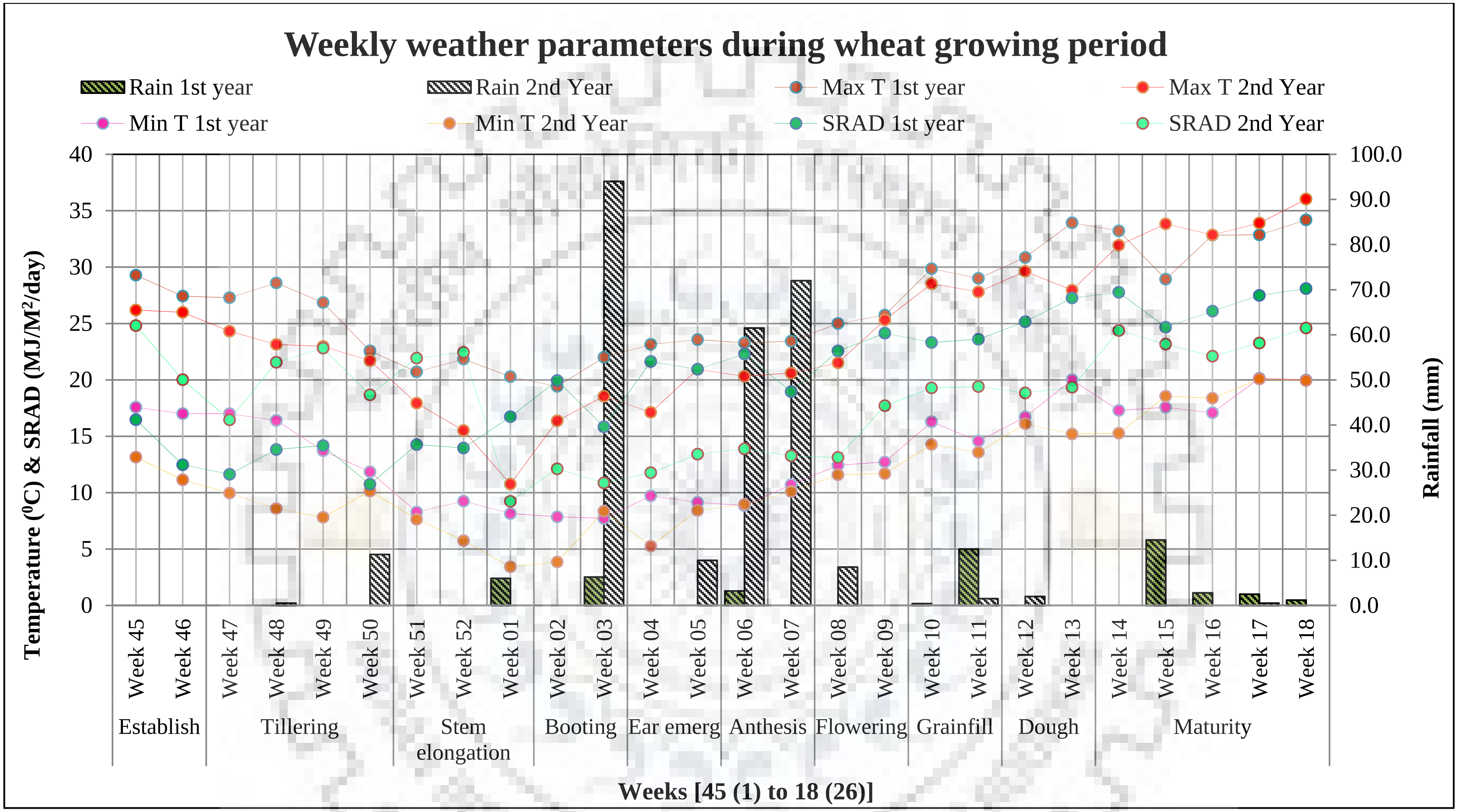


Figure 3.1: Weather condition during crop growing period.

determined using Munsell soil color chart (Colour, 1991). Organic carbon (OC) by Potassium Dichromate method, total nitrogen by Kjheldhal method (Bremner, 1960), available P_2O_5 by Olsen's method (Olsen et al., 1954), available K_2O by Flame photometer (Jackson, 1973) Cation Exchange Capacity (CEC) by acetone extraction method and soil pH was determined using hand held pH meter. Land information on degree of slope, soil depth, and drainage condition and infiltration behavior were measured at the site adopting appropriate methodology.

3.1.4 Experimental design and layout plan

The experiment was laid out using micro plots (2m*2m) in Randomized Block Design (RBD) with 4 treatments of periodical CO_2 application (T_0, T_1, T_2, and T_3) and 3 replications (R_1, R_2, and R_3) during *Rabi* season (November-April) in 2011-12 & 2012-13 (Figure 3.2). Treatment details are mentioned below:

T_0 = Control;

T_1 = CO_2 (700 ± 50 ppm) one application week^{-1} (Monday);

T_2 = CO_2 (700 ± 50 ppm) two applications week^{-1} (Monday & Wednesday);

T_3 = CO_2 (700 ± 50 ppm) three application week^{-1} (Monday, Wednesday& Friday).

3.1.5 Preparation of chamber

Keeping in view the limitations of plant growth in a controlled chamber, micro plot chambers (enclosures) behaving like open top chamber were developed in the experimental field keeping in view to provide near natural condition for plant growth. For this purpose, 1.5 m long iron rods were inserted in the soil at the corner of each micro plot (2m*2m) to keep it upright. Chamber (enclosure) was developed using 120 µ transparent PVC (Polyvinyl chloride) sheet wrapping around the plot with the support of iron rods. The chamber thus prepared was completely open at the top to provide free exchange of temperature or relative humidity etc in the plot. This enclosure also checked the drift loss of applied CO_2 gas from the side. The CO_2 gas at the standard temperature and pressure (15°C, 1 bar) has density of 1.85 kg m^{-3} (1.52 times of the air), therefore the application of CO_2 gas tends to move down towards the ground (Olsson, 2015). There was no risk of gas loss from the top. Field view of chambers is presented in photographs (**Figure 3.3).**

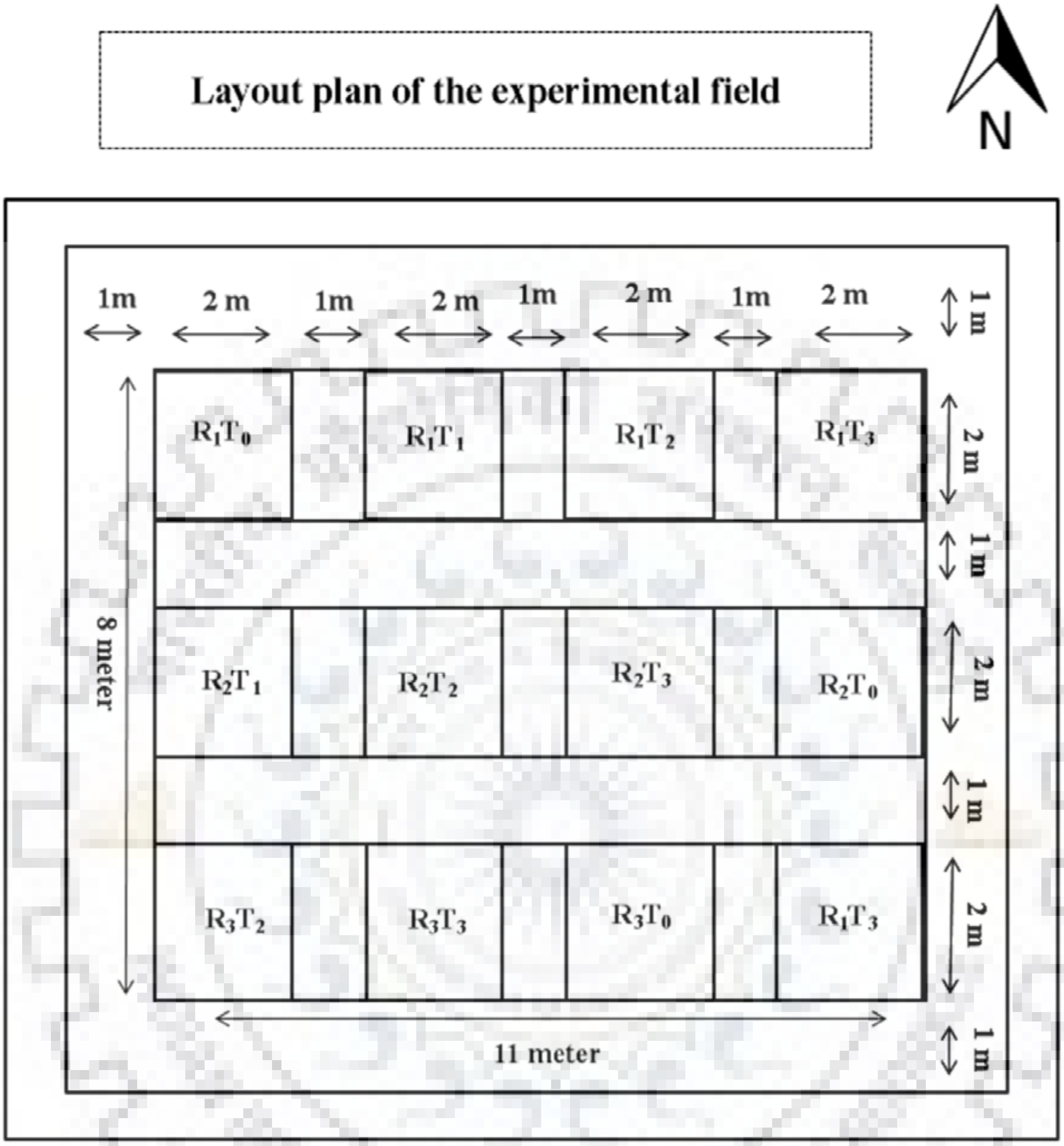


Figure 3.2: Layout of experimental plot

Figure 3.3: Field view of chambers

3.1.6 Schedule of operations

The experimental crop was grown during *Rabi* season (November-April) 2011-12 and 2012-13 and managed adopting recommended package of practices for wheat cultivation in Haridwar district of Uttarakhand. Schedule of various operations are listed in Table 3.1.

Table 3.1: Schedule of field operations during Rabi 2011-12 and 2012-13.

Particulars	Crop	
	2011-12	**2012-13**
General Information's		
Wheat variety	PBW-343	PBW-343
Experimental design	RBD	RBD
Treatments	4	4
Replications	3	3
Treatment combinations	12	12
Total number of plots	12	12
Individual plot size	2m * 2m	2m*2m
Net plot area	11m*8m	11m*8m
Gross area of plot	13m * 10 m	13m * 10 m
Pre sowing operations		
Field leveling	27.10.2011	21.10.2012
Soil sampling	27.10.2011	21.10.2012

Particulars	Crop							
	2011-12				2012-13			
First ploughing	27.10.2011				22.10.2012			
Application of FYM	05.11.2011				30.10.2012			
Second ploughing	06.11.2011				02.11.2012			
Pre sowing irrigation	10.11.2011				05.11.2012			
Third ploughing	23.11.2011				18.11.2012			
Layout	24.11.2011				19.11.2012			
Sowing	25.11.2011				20.11.2012			
Sowing method	Dibbler				Dibbler			
Spacing (row to row)	20 cm				20 cm			
Spacing (plant to plant)	15 cm				15 cm			
Sowing depth	5 cm				5 cm			
Crop management practices								
Irrigation								
Method of application	Flooding				Flooding			
1st irrigation (50 mm)	16.12.2011				11.12.2012			
2nd irrigation (50 mm)	04.01.2012				02.01.2013			
3rd irrigation (50 mm)	15.02.2012				13.03.2013			
4th irrigation (50 mm)	02.03.2012				27.03.2013			
Fertilizer application								
Basal dressing (30:50:50)	25.11.2011				20.11.2012			
1st top dressing (20:0:0)	17.12.2012				13.12.2012			
2nd top dressing (20:0:0)	06.01.2012				04.01.2013			
3rd top dressing (20:0:0)	17.02.2012				10.02.2013			
CO_2 application schedule	**T_0**	**T_1**	**T_2**	**T_3**	**T_0**	**T_1**	**T_2**	**T_3**
1st Application	-	-	-	19/12	-	-	-	17/12
2nd Application	-	-	21/12	21/12	-	-	19/12	19/12
3rd Application	-	23/12	23/12	23/12	-	21/12	19/12	19/12
4th Application	-	-	-	02/01	-	-	-	24/12
5th Application	-	-	04/01	04/01	-	-	26/12	26/12
6th Application	-	06/01	06/01	06/01	-	28/12	28/12	28/12
7th Application	-	-	-	09/01	-	-	-	31/12
8th Application	-	-	11/01	11/01	-	-	02/01	02/01
9th Application	-	13/01	13/01	13/01	-	04/01	04/01	04/01
10th Application	-	-	-	16/01	-	-	-	07/01
11th Application	-	-	18/01	18/01	-	-	09/01	09/01
12th Application	-	20/01	20/01	20/01	-	11/01	11/01	11/01
13th Application	-	-	-	23/01	-	-	-	14/01
14th Application	-	-	25/01	25/01	-	-	16/01	16/01
15th Application	-	27/01	27/01	27/01	-	18/01	18/01	18/01
16th Application	-	-	-	30/01	-	-	-	21/01
17th Application	-	-	01/02	01/02	-	-	23/01	23/01
18th Application	-	03/02	03/02	03/02	-	25/01	25/01	25/01
19th Application	-	-	-	06/02	-	-	-	28/01
20th Application	-	-	08/02	08/02	-	-	30/01	30/01
21st Application	-	10/02	10/02	10/02	-	01/02	01/02	01/02
22nd Application	-	-	-	13/02	-	-	-	04/02

Particulars	Crop							
	2011-12				2012-13			
23rd Application	-	-	15/02	15/02	-	-	06/02	06/02
24th Application	-	17/02	17/02	17/02	-	08/02	08/02	08/02
25th Application	-	-	-	20/02	-	-	-	11/02
26th Application	-	-	22/02	22/02	-	-	13/02	13/02
27th Application	-	24/02	24/02	24/02	-	15/02	15/02	15/02
28th Application	-	-	-	-	-	-	-	18/02
29th Application	-	-	-	-	-	-	20/02	20/02
30th Application	-	-	-	-	-	22/02	22/02	22/02
Plant protection measures								
1st weeding	06.01.2012				01.01.2013			
2nd weeding	04.02.2012				30.01.2013			
Fungicide application (for rust)	-				27.02.2013			
Harvesting	10.04.2012				08.04.2013			
Threshing	11.04.2012				09.04.2013			

3.2 Observations Recorded

3.2.1 Microclimatic observations:

Leaf temperature, canopy temperature and above canopy temperature before and after CO_2 application was recorded using infra-red thermometer. Above canopy CO_2 concentration (ppm) before and after CO_2 enrichment was recorded using hand held CO_2 analyzer.

3.2.1.1 Measurement of CO_2 concentration

As per the treatments and their application schedule, CO_2 gas was applied into respective plots with the help of manifold connected to the fire extinguishing cylinder. The Intergovernmental

Figure 3.4a: CO_2 analyzer

Figure 3.4b: Infra-red thermometer

Panel on Climate Change (IPCC) reported that the global atmospheric CO_2 concentrations would reach to the level of 550 ppm by 2050 and 750 – 1000 ppm by 2100 (Archer, 2011; Soimakallio, 2012). A normalized projection (700 ± 50 ppm) was used in the CO_2 enrichment treatments of wheat crop. The periodical CO_2 enrichment in the experimental plots started in the 3rd week of sowing (crown root initiation stage) and stopped in the 13th week of sowing (flowering stage) so as to avoid any problem with pollinating agent.

The CO_2 concentration (ppm) in the micro plots was recorded using CO_2 gas analyzer Model KM5460 (Figure 3.4a) above the canopy before application, at the time of application and 15 minutes after application. This is a hand held instrument, portable and capable of measuring CO_2 gas in the range of 0 to 9999 ppm with the accuracy of 1ppm.

3.2.1.2 Measurement of temperature

Temperature (^{0}C) of leaf, within the canopy and above the canopy before and after each CO_2 application in the plots was measured using infra-red thermometer (Model IR 330 Eco). This is a handy and portable (Figure 3.4b) instrument.

3.2.2 Growth observations

Plant height (cm), plant dry weight (g per plant), leaf numbers (numbers per plant), leaf length (cm) and leaf width (cm) and tiller count (numbers per plant) are presented in this section.

3.2.2.1 Plant height

The average plant height (cm) from the base to top of the plant was measured in each plot at 20,40,60,80 and 100 days after sowing (DAS) with the help of a meter scale.

3.2.2.2 Plant dry weight

The average plant dry weight (g per plant) was measured at 20,40,60,80 and 100 days after sowing (DAS) by taking two plants from the diagonally opposite direction in the last but one row in each plot. Plant samples thus collected were air and oven (100°C) till the weight became constant.

3.2.2.3 Leaves per plant

The average number of leaves (numbers per plant) from four plants in each plot was measured at 20,40,60,80 and 100 days after sowing (DAS).

3.2.2.4 Leaf length

The average leaf length (cm) from four plants in each plot was measured at 20,40,60,80 and 100 days after sowing (DAS).

3.2.2.5 Leaf width

The average leaf width (cm) from four plants in each plot was measured at 20,40,60,80 and 100 days after sowing (DAS).

3.2.2.6 Tiller count

The average tiller count (numbers per plant) from four plants in each plot was measured at 20,40,60,80 and 100 days after sowing (DAS).

3.2.2.7 Effective tiller

Effective tiller (%) for each plot at each observation was calculated using following formula:

= [Tiller count (final tiller)/ Tiller count (maximum tiller)]*100 ……………. **(3.1)**

3.2.3 Development Observations

Various observations recorded are described in forthcoming paragraphs.

3.2.3.1 Boot leaf stage

Number of days taken to record the expression of boot leaf in 50% plants population in each plot.

3.2.3.2 Anthesis stage

Number of days taken to record the opening of flowers in 50% plants population in each plot.

3.2.3.3 Leaves Area Index

This was calculated for each plot at each observation using following equation:

$$\text{LAI} = \frac{\text{Total leaf area [Plants m}^{-2} \times \text{Leaves plant}^{-1} \times \text{ Leaf length (cm)} \times \text{Leaf width (cm)]}}{100 \times 100} \quad \text{.. } \mathbf{(3.2)}$$

3.2.3.4 Leaf Area Duration (LAD) (days)

LAD is calculated for each plot at each observation using the following equation:

$$LAD = \frac{LAI_1 + LAI_2}{2} \times (t_2 - t_1) \quad \text{………………………………………….. } \mathbf{(3.3)}$$

Where,

LAI_1 = leaf area index on preceding date (t_1);

LAI_2 = leaf area index on succeeding date (t_2);

t_1= preceding date;

t_2= succeeding date.

3.2.3.5 Physiological maturity

Number of days taken to record the hardening of grains in 50% plants population in each plot.

3.2.4 Yield and Yield attribute observations

Various attributes are described in forthcoming paragraphs.

3.2.4.1 Grains per earhead

Ten selected earheads were collected from each plot. This was threshed and cleaned. Seeds were counted and divided by 10 to obtain average number of grains per earhead.

3.2.4.2 Earhead length

Length of 10 selected earheads from each plot was measured and average length was calculated and expressed in cm.

3.2.4.3 Test weight

1000 grains from each plot were weighed and recorded (g. per 1000 grains).

3.2.4.4 Biological yield (kg ha^{-1})

All above the ground dried plant part including grain and straw from each plot was weighed and recorded in kg ha^{-1}.

3.2.4.5 Grain yield (kg ha^{-1})

Cleaned grains from each plot were weighed and recorded in kg ha^{-1}

3.2.4.6 Straw yield (kg ha^{-1})

Straw from each plot were weighed and recorded in kg ha^{-1}

3.2.4.7 Harvest index (%)

This was calculated using the following formula:

$$\text{Harvest index}\,(\%) = \frac{\text{Grain yield}}{\text{Grain} + \text{straw yield}} \times 100 \qquad \ldots\ldots\ldots\ldots \mathbf{(3.4)}$$

3.2.5 Grain Qualitative observation

3.2.5.1 Physical quality traits

3.2.5.1.1 Length of grain (mm)

Length of 10 randomly selected grains from each plot was measured by putting on graph paper and average was calculated and expressed in mm.

3.2.5.1.2 Width of grain (mm)

Width of 10 randomly selected grains from each plot was measured by putting on graph paper and average was calculated and expressed in mm.

3.2.5.2 Biochemical observations

3.2.5.2.1 Carbohydrate estimation

Anthrone method (Dubois and Gilles, 1956):

Sample preparation

- 100 mg of dried sample powder was taken in a conical flask and 10 ml of 80 per cent ethanol was added.
- Contents were boiled on hot water bath for 10 minutes, allowed to settle down and the supernatant was transferred to another dry flask.
- To the residue in the flask, 10 ml of 80 per cent ethanol was added and extracted as before.
- Extraction was repeated again and the final volume was made up to 25 ml with 80 per cent alcohol.
- From this, 5 ml of the extract was taken in a beaker and evaporated on hot water bath (until alcohol smell lost) and made up the volume of the extract to 10 ml (aliquot) with distilled water. This was used for estimating sugar content as follows.
- 0.2 g of anthrone was dissolved in 100 ml of concentrated sulphuric acid. Fresh solution was prepared just before use.

Procedure

- One ml of the aliquot was taken in a test tube. The volume was made up to 2.5 ml with distilled water.
- All the test tube was kept in the ice bath and to which 5 ml of anthrone reagent was added slowly.
- Contents were stirred gently with a glass rod and heated on boiling water bath exactly for 7.5 minutes and cooled immediately on ice bath.
- After cooling, the absorbance of solutions was measured at 630 nm against the blank in a spectrophotometer and the sugar content was calculated through the standard curve.

- Carbohydrate concentration in mg/g of-

DW= {(mg/ml)*dilution factor}/density/volume…………………….. **(3.5)**

3.2.5.2.2 Protein estimation

Bradford method (Bradford, 1976):

- Samples were crushed in 0.1N NaOH and were kept for 30 min. at room temperature.
- Samples were agitated on a vortex mixer and were left to extract for 30 min at room temp.
- Samples were remixed, centrifuged for 5 min at high speed (> 5000g) on a bench centrifuge, and the supernatant solution was decanted.
- Sample were mixed with 5 ml of 1:4 diluted Bradford dye reagent modified by addition of 3 mg/ml soluble polyvinylpyrollidone (PVP).
- After 15 min, an appropriate volume of each replicate was transferred to cuvettes. The absorbance at 595 nm was recorded against the dye reagent/NaOH blank using spectrophotometer.

*Protein concentration in mg/g of DW= {(mg/ml)*dil. factor}/density/volume….* **(3.6)**

3.2.5.2.3 Nitrogen content

Nitrogen estimation in wheat grain was done by Kzeldhal method (Kjeldahl, J. 1883)

3.2.5.2.4 Other macro nutrients

Estimation of (P, K, Ca, Mg and S) was made by using Inductively Coupled Plasma -Mass Spectrometry (ICP-MS) Model Agilent 7900®.Grainsample were prepared as the procedure described by (Yamanka and Fryer, 2001).

3.2.6 Statistical analysis of experimental data

The experimental data recorded during the course of study were statistically analyzed using Analysis of Variance **(**Fisher, 1926**).** The fundamental technique is the partitioning of the total sum of squares SS into components related to the effects used in the model.

$$SS_{Total} = SS_{Treatments} + SS_{Error} \quad \text{………………………………………………}\textbf{(3.7)}$$

The number of degrees of freedom DF can be partitioned in a similar way:

$$DF_{Total} = DF_{Treatments} + DF_{Error} \quad \text{...} \quad \textbf{(3.8)}$$

Mean Sum of squares (MS) for treatments, error and total are calculated by using the formula. Similarly MS is calculated for treatments and error.

$$MS_{Total} = \frac{SS_{Total}}{DF_{Total}} \quad \text{...} \quad \textbf{(3.9)}$$

Then F value is calculated to compare the deviations of two means. It is calculated using formula

$$F_{calc} = \frac{MS_{Treatments}}{MS_{Error}} \quad \text{..} \quad \textbf{(3.10)}$$

Tukey's multiple comparison method is one efficient procedure designed to identify the specific differences that exist among mean responses to several treatments, after the ANOVA has concluded such differences do exist. This result might be useful in supporting decision making.

Test whether there is sufficient evidence at least one of the mean values is different. If so, calculate a critical difference value (CD) between every two means using the formula.

$$CD = q\alpha\,(c, N - c)\sqrt{\frac{MSE}{N}} \quad \text{...} \quad \textbf{(3.11)}$$

Where 'q' is taken from the "Studentized Range" table and is determined by alpha, c (the number of treatments), and N (the total number of observations); n is the sample size of the treatments compared; and MSE is taken from the ANOVA output.

Chapter-4

EXPERIMENTAL RESULTS

Observations recorded and results obtained on soil character, weather condition, micro climatic condition, plant growth & development, yield & yield attributes as well as the quality components of the field experiments entitled "Effect of periodical CO_2 enrichment on wheat *cv.* PBW 343 through Field and Simulation study" are presented in this chapter.

4.1 Soil physical and chemical property

Detailed analysis of soil at different depth has been carried out and results revealed that the soil was sandy loam with textural composition of 12-16% clay, 24-29% silt and 56-58% sand up to a depth of 120 cm. in the same depth of soil, on analysis, it was found that the soil constituent ranges from OC (0-0.6%), Nitrogen (121-134 kg ha^{-1}), Phosphorus (11-16 kg ha^{-1}), and Potassium (210-224 kg ha^{-1}). The soil pH ranges between 6.8-7.8. The CEC, FC, SP and PWP stands at 13-15 cmol kg^{-1}, 0.195-0.224 cm^3cm^{-3}, 0.319-0.414 cm^3cm^{-3}, 0.082-0.121 cm^3cm^{-3} respectively. The soil bulk density which mainly affects the aeration and water holding capacity was measured about 1.42-1.54 g cm^{-3}. Detailed results of all the soil constituents at different soil layers are presented in Table 4.1.

Table 4.1: Physico-chemical properties of experimental field soil.

Depth (cm)	Sand	Silt	Clay	OC	N	P	K	pH	CEC	FC	SP	PWP	BD
	(%)				(Kg ha^{-1})				(cmol kg^{-1})	(cm^3cm^{-3})			(g cm^{-3})
30 (A)	58	24	16	0.6	134	16	224.6	7.8	13	0.224	0.414	0.121	1.54
60 (B_0)	56	27	15	0.4	131	13	221.1	7.3	14	0.208	0.406	0.104	1.50
90 (B_1)	57	29	13	0.1	126	13	212.6	7.3	15	0.201	0.407	0.097	1.49
120 (C)	58	29	12	0	121	11	210.2	6.8	15	0.195	0.319	0.082	1.42

4. 2 Weather Condition

The weather condition during the growing period [45th week (Nov 15) to 18th week (April 15th)] of 2011-12 and 2012-13 is presented in Table 4.2. The total rainfall was recorded as 49.4 and 261.8 mm, the average maximum temperature was recorded as 26.8°C and 24.3 °C, the average minimum temperature was recorded as 13.8 °C and 11.4°C and average solar radiation was recorded as 20.2 and 22.4 MJ m^{-2} day^{-1} during 2011-12 and 2012-13, respectively. In general, the data revealed that the rainfall received during the experimental period is not significant. The temperature is low and also the diurnal variation is high which best suited to wheat cultivation. With respect to 2011-12, ~ 2°C decreases in temperature were noticed during 2012-13, similarly reductive in solar radiation was also noticed which may be attributed to frequent rainfall and cloudy weather. During 2012-13 excessive rainfall at booting and anthesis growth stage proved to be detrimental to the yield of crop probably due to partial lodging and anther washing. Up to 53 percent reduction in wheat yield was noticed by Watson *et al*., (1976) due to water logging at ear emergence. The similar finding was also reported by Niu *et al*., (2016).

Table 4.2: Weather condition during the crop growing period of 2011-12 and 2012-13.

Growth Stages	Week No.	Rain (mm)		Max T (^{0}C)		Min T (^{0}C)		SRAD (MJ m^{-2} day^{-1})	
		2011-12	2012-13	2011-12	2012-13	2011-12	2012-13	2011-12	2012-13
Establishment	Week 45	0.0	0.0	29.3	26.2	17.6	13.1	16.5	24.8
	Week 46	0.0	0.0	27.4	26.0	17.0	11.1	12.5	20.0
Tillering	Week 47	0.0	0.0	27.3	24.3	17.0	10.0	11.6	16.5
	Week 48	0.0	0.5	28.6	23.1	16.4	8.6	13.8	21.6
	Week 49	0.0	0.0	26.9	23.0	13.7	7.8	14.2	22.8
	Week 50	0.0	11.3	22.6	21.7	11.9	10.1	10.7	18.7
Stem elongation	Week 51	0.0	0.0	20.7	17.9	8.3	7.6	14.3	21.9
	Week 52	0.0	0.0	21.8	15.5	9.3	5.8	14.0	22.4
	Week 01	6.0	0.0	20.3	10.8	8.1	3.4	16.7	9.2
Booting	Week 02	0.0	0.0	19.4	16.4	7.9	3.9	19.9	12.1
	Week 03	6.3	94.0	22.0	18.6	7.7	8.4	15.8	10.9
Ear emergence	Week 04	0.0	0.0	23.1	17.1	9.7	5.3	21.6	11.8
	Week 05	0.0	10.0	23.6	20.9	9.1	8.4	20.9	13.4
Anthesis	Week 06	3.2	61.5	23.3	20.3	8.9	9.0	22.3	13.9
	Week 07	0.0	72.0	23.4	20.6	10.7	10.1	19.0	13.3
Flowering	Week 08	0.0	8.5	25.0	21.5	12.4	11.6	22.6	13.1
	Week 09	0.0	0.0	25.8	25.3	12.7	11.7	24.1	17.7
Grain filling	Week 10	0.4	0.0	29.9	28.5	16.3	14.3	23.3	19.3
	Week 11	12.5	1.5	29.0	27.8	14.6	13.6	23.6	19.4
Dough	Week 12	0.0	2.0	30.9	29.6	16.7	16.1	25.2	18.8
	Week 13	0.0	0.0	33.9	28.0	20.0	15.2	27.3	19.3
Maturity	Week 14	0.0	0.0	33.2	31.9	17.3	15.3	27.8	24.4
	Week 15	14.5	0.0	28.9	33.8	17.6	18.6	24.7	23.2
	Week 16	2.8	0.0	32.8	32.9	17.1	18.4	26.1	22.1
	Week 17	2.5	0.5	32.9	33.9	20.1	20.1	27.5	23.3
	Week 18	1.2	0.0	34.2	36.0	20.0	19.9	28.1	24.6
Sum/Average		**49.4**	**261.8**	**26.8**	**24.3**	**13.8**	**11.4**	**20.2**	**18.4**

4. 3 CO_2 enrichment and crop micro climate (temperature and CO_2) change

The average temperature of leaf, within canopy and above the canopy before and after the CO_2 enrichment of wheat *cv*. PBW 343 is presented in Table 4.3a and Table 4.3b. Data pertaining to microclimate *i.e.* average leaf temperature (°C), within canopy air temperature (°C) and above canopy temperature (°C) during 2011-12, was 16.5 °C, 21.2 °C and 21.1 °C before CO_2 enrichment whereas during 2012-13 significant decrease were noticed in all these parameters. The average leaf temperature (°C), within canopy air temperature (°C) and above canopy temperature (°C) during 2012-13 was 15.4 °C, 18.2 °C and 18.1 °C respectively. Similar patterns of reduction in microclimate were observed after the application of CO_2.

Average of both years indicate that the leaf temperature, within canopy air temperature and canopy air temperature increases by 0.2^0 C, 0.4 ^{0}C and 0.2 ^{0}C respectively. Practically there was no abnormality shown by the crop with such a change in temperature regime probably this increase was purely temporary in nature as the crop was grown under the open field condition. Increase in leaf temperature after CO_2 application may be due to decreased stomatal conductance and latent heat loss (Cannell and Thornley, 1998; Allen Jr and Prasad, 2004; Ainsworth and Rogers 2007). Air temperature within canopy has also been reported to increase by 0.6 – 1.0 ^{0}C with CO_2 enrichment up to 550 ppm in wheat and rice (Pinter *et al*., 2000, Pal *et al.* 2012d). It may be due to reduced stomatal aperture of plant leaf (Cho & Oki, 2012).

Table 4.3a: Average leaf temperature (ºC), within canopy air temperature (°C) and above canopy temperature (ºC) before and after CO_2 enrichment of Wheat *cv*. PBW 343.

Treatments	Leaf temperature (ºC)			Within canopy air temperature (ºC)			Above canopy air temperature (ºC)		
	2011-12	2012-13	Mean	2011-12	2012-13	Mean	2011-12	2012-13	Mean
	Before CO_2 application								
T_0	16.4	15.4	15.9	21.2	18.2	19.7	21.2	18	19.6
T_1	16.6	15.3	15.9	21.4	18.1	19.8	21.4	18.2	19.8
T_2	16.5	15.3	15.9	21	18.2	19.6	21	18.1	19.6
T_3	16.6	15.5	16	21	18.2	19.6	20.9	18.2	19.6
Mean	16.5	15.4	15.9	21.2	18.2	19.7	21.1	18.1	19.6
	After CO_2 application								
T_0	16.5	15.6	16.1	21.2	18.2	19.7	21.2	18	19.6
T_1	16.6	15.5	16.1	21.5	18.8	20.2	21.4	18.4	19.9
T_2	16.7	15.5	16.1	21.5	18.7	20.1	21.3	18.3	19.8
T_3	16.6	15.6	16.1	21.4	18.9	20.2	21.6	18.5	20.1
Mean	16.6	15.6	16.1	21.4	18.7	20	21.4	18.3	19.8
Change (°C)	**0.1**	**0.2**	**0.2**	**0.3**	**0.5**	**0.4**	**0.3**	**0.2**	**0.2**

Table 4.3b: Average CO_2 concentration before, after and at the time of CO_2 enrichment of wheat *cv.* PBW 343.

Treatment	CO_2 concentration (ppm)								
	Before application			At the time of application			15 minutes after application		
	2011-12	2012-13	Mean	2011-12	2012-13	Mean	2011-12	2012-13	Mean
T_0	309	320	315	308	321	314	310	326	318
T_1	308	317	313	767	787	777	554	567	561
T_2	308	320	314	764	779	772	562	568	565
T_3	309	319	314	775	791	783	584	565	575
Average	**309**	**319**	**314**	**653**	**669**	**661**	**503**	**507**	**505**

The average CO_2 concentration before and after CO_2 enrichment as well as at the time of enrichment is presented in Table 4.3b. The average ambient CO_2 concentration in the experimental plot was recorded as 309 ppm during 2011-12 and 319 ppm during 2012-13. Observations recorded also showed that at the time of application the CO_2 level rose to about 650 ± 10 ppm which came down to 500±10 ppm after 15 minutes of application. General observation was that the CO_2 level in the treated plot subsided to become normal (almost equivalent to ambient) within 20 minute. It may be due to increased intake rate of CO_2 in the plants (Kimball *et al.*, 1993, Keenan *et al.*, 2016) and settlement on the ground. Treatment wise observations pertaining to microclimate is presented in Annexure 4.

4.4 Effect of CO_2 Enrichment on Wheat Crop Growth, Development, Yield and Yield Attributes

Beneficial response of CO_2 application on wheat crop grown under controlled condition has been reported from different parts of the world. Observations recorded in this study under field condition are presented in the forth coming paragraphs.

4.4.1. Plant height (cm)

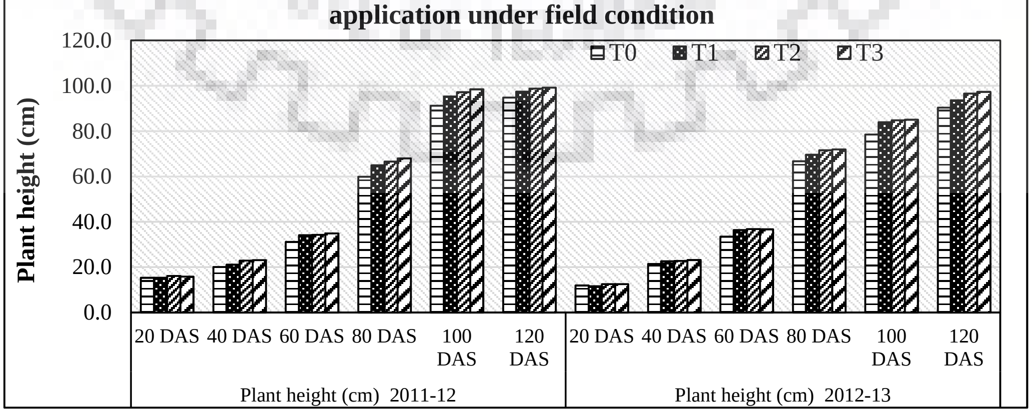
Statistical analysis pertaining to plant height (cm) as affected by different CO_2 treatments in wheat crop *cv.* PBW 343 is presented in Table-4.4.1and graphically depicted in Figure 4.1. Result revealed that during the year 2011-12 significant difference in plant height between the treatments was recorded at 40, 60, 80 and 100 days after sowing whereas, during 2012-13 significant difference was observed only at 60, 80 and 100 DAS. During 2011-12 the average plant height at 20, 40, 60, 80,100 and 120 days was 15.7, 21.8, 33.6, 64.9, 95.6 and 97.6 cm whereas, during 2012-13 it was 12.2, 22.5, 35.9, 70, 83.1 and 94.5 cm respectively.

Table 4.4.1: Plant height of wheat *cv*. PBW 343 affected by periodical CO_2 enrichment

Treatments	Plant height (cm) days after sowing					
	20	40	60	80	100	120
2011-12						
T_0	15.3	20.1	31.1	59.9	91.2	94.8
T_1	15.3	21.1	34.1	65.0	95.3	97.4
T_2	16.1	22.9	34.2	66.6	97.2	98.8
T_3	15.9	23.1	34.9	68.0	98.4	99.2
Mean	15.7	21.8	33.6	64.9	95.6	97.6
P=0.05	NS	Sig*	Sig **	Sig *	Sig **	NS
SE±	-	1.92	1.89	2.07	1.13	-
CD	-	0.88	0.86	4.55	2.49	-
2012-13						
T_0	12.0	21.4	33.5	66.7	78.6	93.4
T_1	11.6	22.7	36.4	69.6	83.9	93.6
T_2	12.6	22.8	36.8	71.6	84.8	96.6
T_3	12.6	23.2	36.7	72.0	85.1	97.4
Mean	12.2	22.5	35.9	70.0	83.1	94.5
Sig	NS	NS	Sig*	Sig **	Sig *	NS
SE±	-	-	1.2	1.09	1.99	-
CD	-	-	2.65	2.4	4.37	-

Overall, result indicates that the plant height was significantly increased in both the years at 60, 80 and 100 DAS. Plant height, in general in descending order was recorded as T_3, T_2, $T_1$and T_0. It was increased with advancing of age. Average height (2011-12 and 2012-13) was recorded as 14.0 cm, 22.2 cm, 34.8 cm, 67.5 cm, 89.4 cm and 96.1 at 20, 40, 60, 80, 100 and 120 DAS respectively. It was remarkably increased under elevated CO_2 treatments by each increase in CO_2 levels. The average increase in the plant height was recorded up to 13.5% in 2011-12 and 8.5 % in 2012-13.

Figure 4.1 : Plant height of Wheat *cv*. PBW 343 as affected by CO_2 application under field condition



Increased plant height with CO_2 enrichment has already been reported (Mulholland, *et al.* 1997; Wu *et al.* 2004; Pal, *et al.* 2005; Qiao, *et al.* 2010).

4.4.2 Tiller per plant

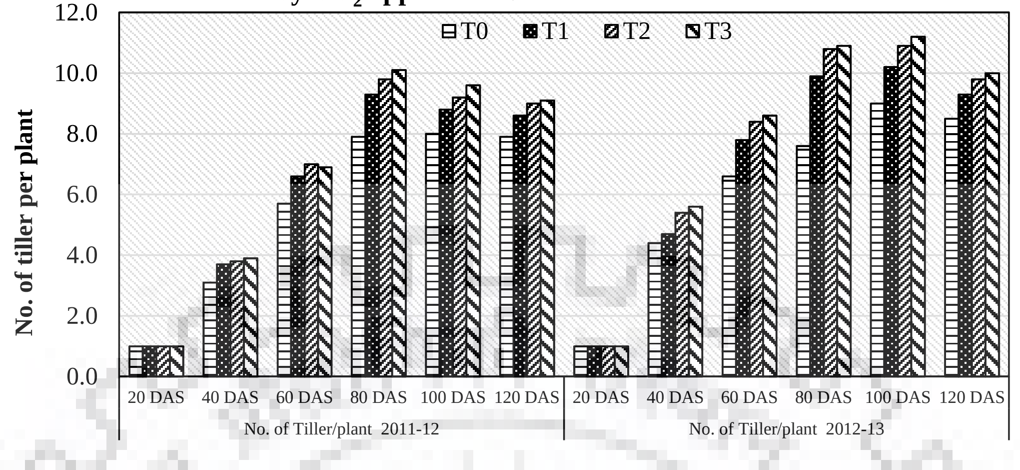
Tiller count as affected by different CO_2 treatments in wheat crop *cv.* PBW 343 is presented in Table-4.4.2 and graphically depicted in Figure 4.2. Result revealed that during the year 2011-12 significant difference between the treatments was recorded at 60, 80 and 100 days after sowing whereas during 2012-13 the difference was significant at 40, 60 80 and 100 DAS.

Table 4.4.2: Tiller per plant in wheat *cv.* PBW 343 as affected by periodical CO_2 enrichment.

Treatments	**Tillers plant^{-1}, days after sowing**					
	20	**40**	**60**	**80**	**100**	**120**
	2011-12					
T_0	1	3.1	5.7	7.9	8.0	7.9
T_1	1	3.7	6.6	9.3	8.8	8.6
T_2	1	3.8	7	9.8	9.2	9
T_3	1	3.9	6.9	10.1	9.6	9.1
Mean	1	3.6	6.5	9.3	8.9	8.6
P=0.05	NS	NS	Sig *	Sig **	Sig *	NS
SE±	-	-	0.4	0.5	0.5	-
CD	-	-	0.9	1.1	1.1	-
2012-13						
T_0	1	4.4	6.6	7.6	9.0	8.5
T_1	1	4.7	7.8	9.9	10.2	9.3
T_2	1	5.4	8.4	10.8	10.9	9.8
T_3	1	5.6	8.6	10.9	11.2	10
Mean	1	5.1	7.8	9.8	10.3	9.4
P=0.05	NS	Sig*	Sig *	Sig *	Sig **	NS
SE±	-	0.5	0.7	1.2	0.7	-
CD	-	1	1.5	2.7	1.6	-

During 2011-12 the average tiller count at 20, 40, 60, 80,100 and 120 days was 1, 3.6, 6.5, 9.3, 8.9 and 8.6 whereas, during 2012-13 it was 1.0, 5.1, 7.8, 9.8, 10.3 and 9.4 respectively. Significant change in tiller count was noticed at 60, 80 and 100 days after sowing. In general the tiller count increased with advancing of age and the average was recorded as 1.0, 4.4, 7.2, 9.6 and, 9.5 at 20, 40, 60, 80 and 100 DAS respectively. Average (2011-12 and 2012-13) increase of tiller count in T_3 (over the control) was recorded up to 35.6 % at 80 DAS.

Figure 4.2 : No of tiller per plant of Wheat *cv.* PBW 343 as affected by CO_2 application under field condition



The increased tiller count with CO_2 enrichment has already been reported (Pal, *et al*., 2005; Mulholland *et al*., 1997; Mishra *et al*., 2013; Jia *et al*., 2016).

4.4.3 Average leaf numbers per plant

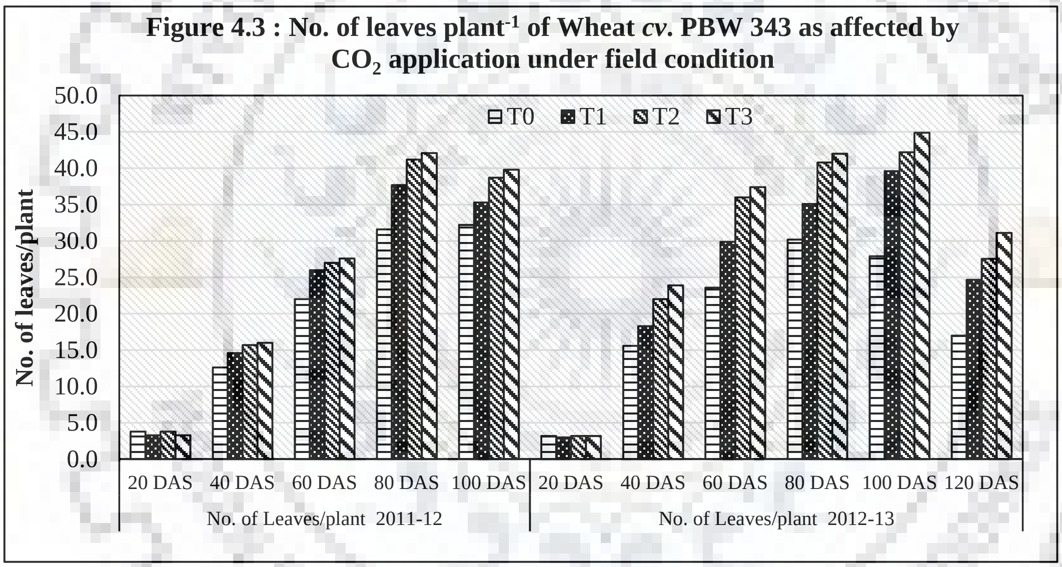
Statistical analysis of data pertaining to leaf count per plant as affected by different CO_2 treatments in wheat crop *cv*. PBW 343 is presented in Table-4.4.3 and graphically depicted in Figure 4.3. Result revealed that the difference between the treatments was significant at 60, 80 and 100 days after sowing, during both the years.

Table 4.4.3: Leaves per plant in wheat *cv*. PBW 343 as affected by periodical CO_2 enrichment.

Treatments	Leaves per plant, days after sowing				
	20	40	60	80	100
2011-12					
T_0	3.8	12.6	22	31.6	32.2
T_1	3.3	14.6	26	37.7	35.3
T_2	3.8	15.7	27	41.2	38.7
T_3	3.3	16	27.6	42.1	39.8
Mean	3.6	14.7	25.6	38.1	36.5
P=0.05	NS	NS	Sig**	Sig ***	Sig **
SE±	-	-	1	0.6	1.7
CD	-	-	2.3	1.2	3.7
2012-13					
T_0	3.2	15.6	23.6	30.2	27.9
T_1	3	18.3	29.9	35.1	39.6
T_2	3.2	22	36	40.8	42.2
T_3	3.2	23.9	37.4	42	44.9
Mean	3.2	19.9	31.7	37	38.7
Sig	NS	NS	Sig **	Sig *	Sig *

Treatments	Leaves per plant, days after sowing				
	20	40	60	80	100
SE±	-	-	2.4	3.1	5.2
CD	-	-	5.2	6.8	11.4

During 2011-12 the average leaf count at 20, 40, 60, 80 and 100 days was 3.6, 14.7, 25.6, 38.1 and 36.5 whereas, during 2012-13 it was 3.2, 19.9, 31.7, 37 and 38.7 respectively. The leaf count significantly increased by CO_2 enrichment over control. The two year average leaf count was recorded as 3.3, 17.2, 28.7, 37.6and 37.5 at 20, 40, 60 80 and100 DAS respectively. The average increase in leaf count (over the control) with CO_2 enrichment was recorded as 33% during 2011-12 and 61% during 2012-13 and two year average was 47 % at 80 days after sowing.



The increase in leaf count in wheat with CO_2 enrichment has already been reported (Kaddour and Fuller, 2004; Li *et.al*., 2007; Karen *et.al*., 2015).

4.4.4 Average leaf length (cm)

Statistical analysis of data pertaining to leaf length as affected by different CO_2 treatments in wheat crop *cv.* PBW 343 is presented in Table-4.4.4 and graphically depicted in Figure 4.4. Result indicates that, during the year 2011-12 significant difference between the treatments was recorded at 60, 80 and 100 DAS whereas during 2012-13 the difference was significant at 80 and 100 DAS. During 2011-12 the average leaf count at 20, 40, 60, 80 and 100 days was 13.8, 19.5, 23.9, 30.7 and 29.3 cm whereas, during 2012-13 it was 10.1, 19.4, 28.2, 26.5 and 25.5

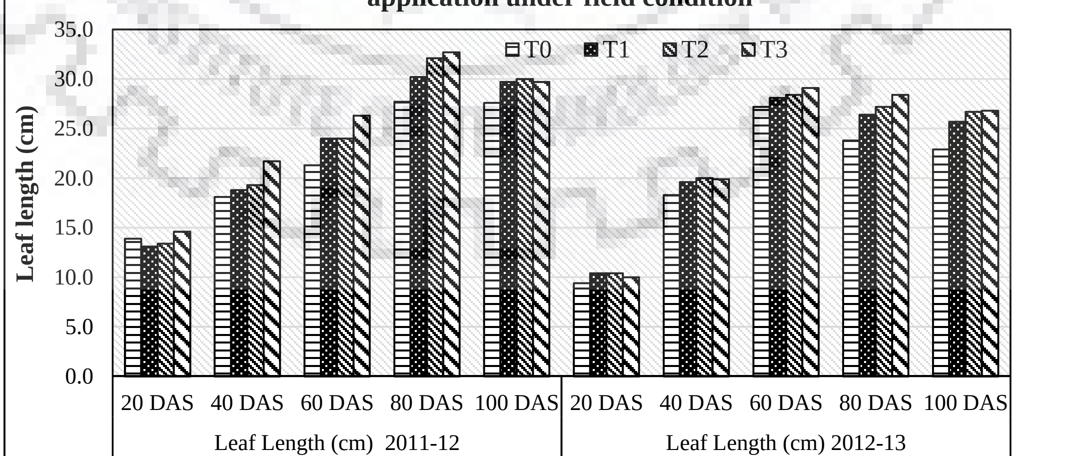
cm respectively. Analysis revealed that the leaf length was significantly changes in both the years with each increase in CO_2 levels.

Table 4.3.4: Leaf length in wheat *cv.* PBW 343 as affected by periodical CO_2 enrichment

Treatments	Leaf length (cm) , days after sowing				
	20	40	60	80	100
2011-12					
T_0	13.9	18.1	21.3	27.7	27.6
T_1	13.1	18.8	24	30.2	29.7
T_2	13.4	19.3	24	32.1	30
T_3	14.6	21.7	26.3	32.7	29.7
Mean	13.8	19.5	23.9	30.7	29.3
P=0.05	NS	Sig *	Sig *	Sig *	NS
SE±	-	0.95	1.36	1.7	-
CD	-	2.1	2.99	3.75	-
2012-13					
T_0	9.4	18.3	27.2	23.8	22.9
T_1	10.4	19.6	28.1	26.4	25.7
T_2	10.4	20	28.4	27.2	26.7
T_3	10	19.9	29.1	28.4	26.8
Mean	10.1	19.4	28.2	26.5	25.5
Sig	NS	NS	NS	Sig *	Sig *
SE±	-	-	-	1.46	1.28
CD	-	-	-	3.22	2.81

Leaf length in general in descending order was recorded as T_3, T_2, T_1 and T_0. The average of two years was recorded as 12.1, 19.5, 26.1, 28.6 and 27.4 cm at 20, 40, 60, 80 and 100 DAS respectively.

Figure 4.4: Leaf length (cm) of wheat *cv.* PBW 343 as affected by CO_2 application under field condition



The increased leaf size in wheat with CO_2 enrichment has already been reported (Masle, 2000; Franks and Beerling 2009).

4.4.5 Average leaf width (cm)

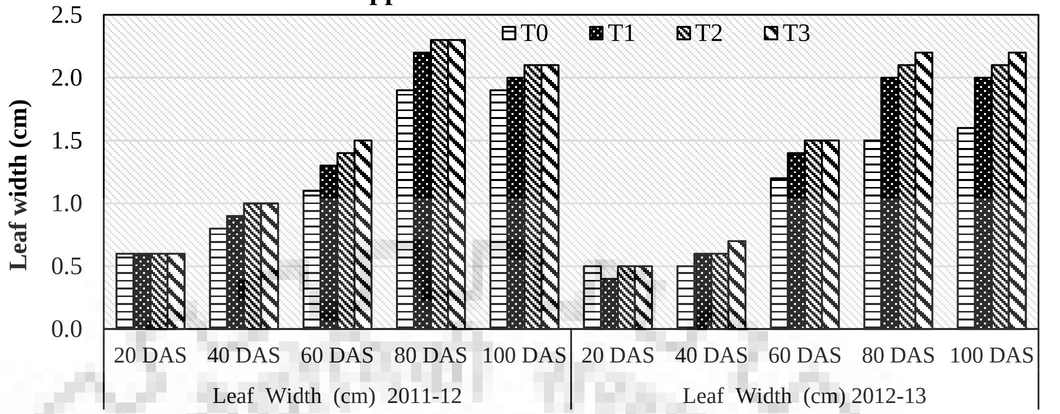
Statistical analysis of data pertaining to leaf width as affected by different CO_2 treatments in wheat crop *cv.* PBW 343 is presented in Table-4.4.5 and graphically depicted in Figure 4.5. Result revealed that the significant difference in leaf width between the treatments was recorded at 40, 60 and 80 days after sowing in both the years. In general, leaf width was recorded in descending order under T_3, T_2, and T_1 & T_0. During 2011-12 the average leaf count at 20, 40, 60, 80 and 100 days was 0.6, 0.9, 1.3, 2.2 and 2.0 cm whereas, whereas during 2012-13 it was 0.5, 0.6, 1.4, 2.0 and 2.0 cm respectively.

Table 4.4.5: Leaf width (cm) of wheat *cv.* PBW 343 as affected by periodical CO_2 enrichment.

Treatments	Leaf width (cm) , days after sowing				
	20	**40**	**60**	**80**	**100**
2011-12					
T_0	0.6	0.8	1.1	1.9	1.9
T_1	0.6	0.9	1.3	2.2	2.0
T_2	0.6	1.0	1.4	2.3	2.1
T_3	0.6	1.0	1.5	2.3	2.1
Mean	0.6	0.9	1.3	2.2	2.0
P=0.05	NS	Sig *	Sig **	Sig *	NS
SE±	-	0.05	0.08	0.12	-
CD	-	0.10	0.18	0.26	-
2012-13					
T_0	0.5	0.5	1.2	1.5	1.6
T_1	0.4	0.6	1.4	2.0	2.0
T_2	0.5	0.6	1.5	2.1	2.1
T_3	0.5	0.7	1.5	2.2	2.2
Mean	0.5	0.6	1.4	2.0	2.0
Sig	NS	Sig *	Sig **	Sig **	NS
SE±	-	0.05	0.07	0.15	-
CD	-	0.10	0.15	0.34	-

Average leaf width was recorded as 0.55, 0.75, 1.4, 2.2 and 2.0 cm at 20, 40, 60, 80 and 100 DAS respectively.

Figure 4.5: Leaf width (cm) of wheat *cv.* PBW 343 as affected by CO_2 application under field condition



Increase in leaf size of wheat due to CO_2 enrichment might have been caused due to increased photosynthesis (Masle, 2000 and Franks and Beerling, 2009).

4.4.6 Leaf Area Index (LAI)

Statistical analysis of data pertaining to LAI as affected by different CO_2 treatments in wheat crop *cv.* PBW 343 is presented in Table-4.4.6 and graphically depicted in Figure 4.6. Result revealed that the significant difference in LAI between the treatments was recorded at 40, 60 and 80 days after sowing in both the years which is attributed to increased leaf number, leaf length and width. During 2011-12 the average LAI at 20, 40, 60, 80 and 100 days was 0.07, 0.5, 2.1, 5.4 and 5.1 whereas, during 2012-13 it was 0.04, 0.38, 2.8 5, 5.0 and 4.7 respectively. LAI in general in descending order was recorded as T_3, T_2, T_1 and T_0. Analysis revealed that LAI was increased with advancing of age, the two year average was recorded as 0.06, 0.44, 2.45, 5.2 and 4.9 at 20, 40, 60, 80and 100 DAS respectively.

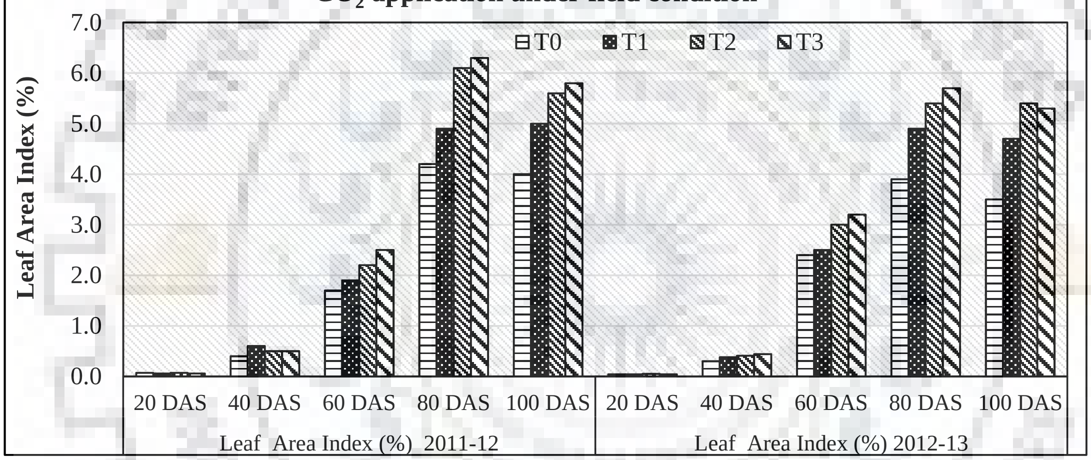
Table 4.4.6: Leaf Area Index of wheat *cv.* PBW 343 as affected by periodical CO_2 enrichment.

Treatments	Leaf Area Index, days after sowing				
	20	40	60	80	100
2011-12					
T_0	0.07	0.4	1.7	4.2	4.0
T_1	0.06	0.6	1.9	4.9	5.0
T_2	0.07	0.5	2.2	6.1	5.6
T_3	0.06	0.5	2.5	6.3	5.8
Mean	0.07	0.5	2.1	5.4	5.1
P=0.05	NS	Sig *	Sig **	Sig *	NS
SE±	-	0.1	0.2	0.3	-
CD	-	0.1	0.4	0.6	-
2012-13					
T_0	0.04	0.3	2.4	3.9	3.5

Treatments	Leaf Area Index, days after sowing				
	20	**40**	**60**	**80**	**100**
T_1	0.04	0.38	2.5	4.9	4.7
T_2	0.05	0.41	3.0	5.4	5.4
T_3	0.04	0.44	3.2	5.7	5.3
Mean	0.04	0.38	2.8	5.0	4.7
Sig	NS	Sig *	Sig *	Sig **	NS
SE±	-	0.05	0.2	0.4	-
CD	-	0.1	0.2	0.9	-

Two year average LAI was increased by 52.5 % in T_3 over T_0. It may be attributed to increased number of tillers which hold up the leaves, resulting higher leaf area (Lawlor and Mitchell, 1991).

Figure 4.6: Leaf Area Index (%) of wheat *cv*. PBW 343 as affected by CO_2 application under field condition



Result is in agreement with the findings already reported (Pleijel *et al.* 2000; Ewert *et al.* 2002; Long *et al.* 2005; Li, *et al.* 2007; Thilakarathne *et al.* 2013).

4.4.7 Flag leaf size

Data of flag leaf length (cm), width (cm) and area (cm^2) of wheat variety PBW 343 is presented in Table 4.4.7. A cursory glance over result revealed that the significant difference in flag leaf length was recorded at 80 DAS during 2011-12 and 80 and 100 DAS during 2012-13 whereas flag leaf area (cm^2) was significantly increased at 80 DAS in 2011-12 and at 100 DAS in both the years. The flag leaf length (cm), width (cm) and area (cm^2) recorded in descending order was T_3>T_2>T_1>T_0 in both the years. Two year average flag leaf length was recorded as 30.5 cm and 30.2 cm; width 2.3 and 2.7 cm and area was 81.5 cm^2 and 69.5 cm^2 at 80 and 100 DAS during the year 2011-12 and 2012-13 respectively.

Table 4.4.7: Flag Leaf length, breadth and area of Wheat cv. PBW 343 as affected by periodical CO_2 enrichment

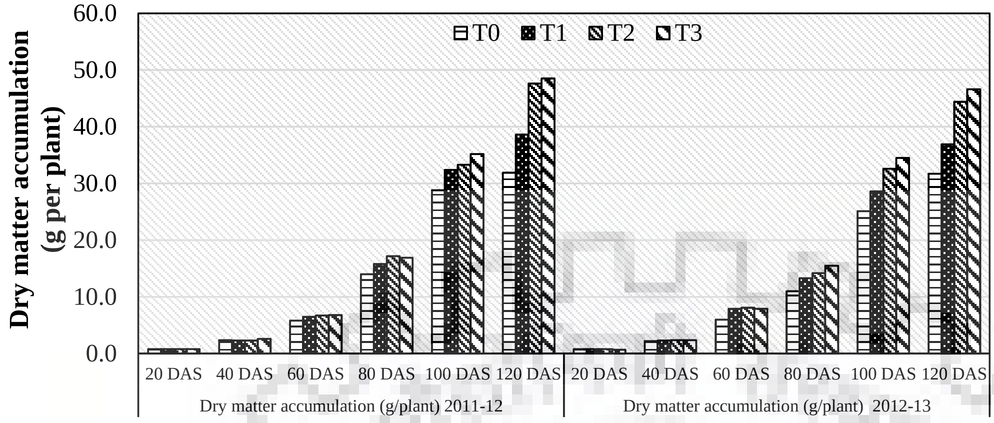
Treatments	Flag Leaf					
	Length (cm)	Width (cm)	Length (cm)	Width (cm)	Flag leaf area (cm^2)	
	80 DAS		100 DAS		80 DAS	100 DAS
2011-12						
T_0	28.5	2.1	28.9	2.7	60.1	78.1
T_1	29.7	2.2	30.7	2.9	65.2	89
T_2	29.6	2.6	29.9	2.9	76.9	87.7
T_3	30.9	2.7	31.1	3	83.4	92.4
Mean	29.7	2.4	30.2	2.9	71.4	86.8
P=0.05	NS	Sig*	NS	NS	Sig*	NS
SE±	-	0.2	-	-	6.6	-
CD	-	0.4	-	-	14.5	-
2012-13						
T_0	29.2	2	29.4	2.2	58.3	64.7
T_1	30.8	2.3	31.2	2.4	69.8	75
T_2	31.5	2.3	31.4	2.5	71.5	78.5
T_3	31.8	2.3	31.9	2.7	74.1	86.2
Mean	30.8	2.2	31	2.5	68.4	76.1
Sig	Sig *	NS	Sig **	Sig **	Sig *	Sig **
SE±	0.7	-	0.6	0.1	4.1	4
CD	1.4	-	1.3	0.2	9.1	8.7

Increased flag leaf area due to CO_2 enrichment is in agreement with previous findings (Fangmeier *et al.* 1997; Mayeux *et al.* 1997; Kant *et al.* 2012; Biswas *et al.* 2013).

4.4.8 Plant dry matter (g plant^{-1})

Statistical analysis of data pertaining to plant dry matter at 20, 40, 60, 80, 100 and 120 DAS and panicle dry weight at 100 and 120 DAS are presented in Table 4.4.8 and graphically depicted in Figure 4.7. In respect to plant dry matter (g plant^{-1}) significant difference between the treatments was recorded at 60, 80, 100 and 120 DAS in both the years. In general the response was recorded in descending order as T_3>T_2>T_1>T_0 in both the years. During 2011-12 the average plant dry matter at 20, 40, 60, 80, 100 and 120 was 0.8, 2.4, 6.5, 16.0, 32.4 and 41.7 g whereas, during 2012-13 it was 0.8, 2.3, 7.5, 13.5, 30.2 and 39.9 g, respectively. The average plant dry weight (g plant^{-1}) of the two years was recorded as 0.8, 2.4, 7.0, 14.8, 31.3 and 40.8 g plant^{-1} at 20, 40, 60, 80, 100 and 120 DAS, respectively.

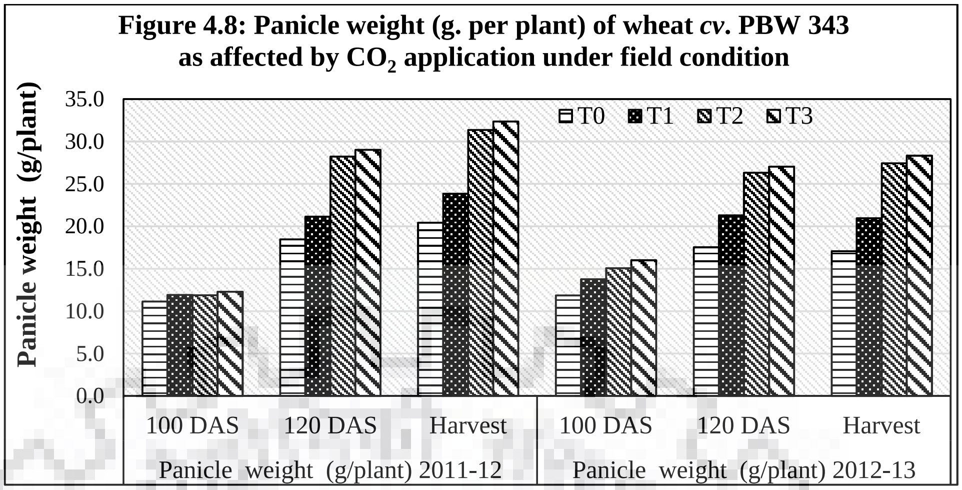
Figure 4.7: Dry matter accumulation (g per plant) of wheat *cv.* PBW 343 as affected by CO_2 application under field condition



Two years average dry matter was increased up to 49.5%. Increased total dry matter accumulation was attributed to increased photosynthates accumulation, resulting increased leaf number, size and tiller numbers per plant which contributes towards total dry matter. Similar findings have already been reported (Yang *et al.*, 2006; Li *et al.*, 2007; Kant *et al.*, 2012; Leakey *et al.*, 2009; Dahal *et al.*, 2014).

Table 4.4.8: Dry matter accumulation (g per plant) and Panicle weight (g per plant) of wheat *cv.* PBW 343 as affected by periodical CO_2 enrichment

Treatments	Dry weight (g $plant^{-1}$), days after sowing						Panicle weight (g $plant^{-1}$)		
	20	40	60	80	100	120	100 DAS	120 DAS	Harvest
2011-12									
T_0	0.8	2.4	5.8	14	28.8	31.9	11.1	18.5	20.4
T_1	0.8	2.3	6.5	15.8	32.4	38.6	11.9	21.1	23.8
T_2	0.8	2.3	6.7	17.2	33.3	47.6	11.9	28.2	31.4
T_3	0.8	2.6	6.8	16.9	35.2	48.5	12.3	29	32.4
Mean	0.8	2.4	6.5	16	32.4	41.7	11.8	24.2	27
P=0.05	NS	NS	Sig***	Sig ***	Sig **	Sig **	Sig *	Sig ***	Sig ***
SE±	-	-	0.1	0.7	0.7	0.3	0.4	0.4	0.3
CD	-	-	0.3	1.5	1.5	3.7	0.8	0.8	0.6
2012-13									
T_0	0.8	2.2	6	11	25.1	31.7	11.9	17.5	17.1
T_1	0.8	2.3	7.9	13.3	28.6	36.9	13.8	21.3	21
T_2	0.8	2.4	8.1	14.2	32.6	44.4	15.1	26.3	27.5
T_3	0.7	2.4	7.9	15.5	34.5	46.6	16	27	28.3
Mean	0.8	2.3	7.5	13.5	30.2	39.9	14.2	23.1	23.5
Sig	NS	NS	Sig ***	Sig **	Sig ***	Sig ***	Sig *	Sig **	Sig **
SE±	-	-	0.2	0.7	1.4	2.4	1.3	2.2	0.7
CD	-	-	0.5	1.5	3.1	5.2	2.8	4.9	1.5



Similarly, per panicle weight (Figure 4.8) was also increased significantly by CO_2 enrichment. The average per panicle weight was 11.8, 24.2 and 27 g per panicle during 2011-12, whereas it was 14.2, 23.1 and 23.5 g per panicle during 2012-13 at 80 DAS, 100 DAS and at harvest stage. Treatment response trend in panicle weight was recorded similar to plant dry matter weight.

4.4.9 Phenological expressions

Days taken to attain the phenological stages such as boot leaf initiation, ear emergence, anthesis, flowering and physiological maturity are presented in Table 4.4.9. Observations revealed that the days taken to boot leaf initiation, ear emergence, anthesis, flowering and physiological maturity was marginally reduced by periodical CO_2 enrichment. Average number of days taken to initiate boot leaf, ear emergence, anthesis, flowering and physiological maturity was recorded as 75, 82, 91, 98 and 135 days during 2011-12 whereas 80, 88, 96, 101 and 136 during 2012-13 respectively.

Table 4.4.9: Phenological expression of Wheat *cv.* PBW 343 as affected by periodical CO_2 enrichment

Treatments	**Days taken to express in 50% plant population**				
	Boot leaf initiation	**Ear emergence**	**Anthesis**	**Flowering**	**Physiological maturity**
			2011-12		
T_0	76	84	93	100	136
T_1	74	82	92	98	136
T_2	74	82	91	98	134
T_3	74	80	90	97	134
Mean	75	82	91	98	135
P=0.05	Sig***	NS	NS	NS	Sig***
SE±	0.3	-	-	-	0.3

Treatments	Days taken to express in 50% plant population				
	Boot leaf initiation	Ear emergence	Anthesis	Flowering	Physiological maturity
CD	0.6	-	-	-	0.7
2012-13					
T_0	81	89	97	103	138
T_1	80	88	96	100	135
T_2	80	88	95	100	136
T_3	79	87	96	99	135
Mean	80	88	96	101	136
Sig	NS	NS	NS	NS	Sig*
SE±	-	-	-	-	0.8
CD	-	-	-	-	1.8

Physiological maturity was delays by 2-3 days in both the years. Reduction in days taken to various phenological expressions was observed as CO_2 level increased this might be attributed to enhanced photosynthetic rate resulting faster growth. The result was in close proximity with the finding of (Bishnoi *et al.*, 1995; Ewert *et al.*, 2002; Dass *et al.*, 2012 and Pal *et al.* 2013).

4.4.10 Leaf area duration (days)

Leaf Area Duration (LAD) as affected by various CO_2 treatments was calculated for 0-20 days, 20-40 days, 40-60 days, 60-80 days, 80-100 days and 100-120 days and presented in Table **4.4.10**. Data for the year 2011-12 and 2012-13 revealed that the significant increase in LAD was observed by each increase in CO_2 levels. During 2011-12 the average LAD at 20, 40, 60, 80, 100 and 120 was 0.6, 5.7, 25.8, 74.5, 104.8 and 72.8 days whereas, during 2012-13 it was 0.4, 4.3, 31.6, 77.5, 96.8 and 67.3 days respectively.

Table 4.4.10: Leaf Area Duration (LAD) in days of Wheat cv. PBW 343 as affected by CO_2 application under field condition

Treatments	Leaf Area Duration (day)						
	20 D	40	60	80	100	120	Total
2011-12							
T_0	0.7	4.7	21.0	59.0	82.0	58.0	225.4
T_1	0.6	6.6	25.0	68.0	99.0	71.0	270.2
T_2	0.7	5.7	27.0	83.0	117.0	80.0	313.0
T_3	0.6	5.6	30.0	88.0	121.0	83.0	328.2
Mean	0.6	5.7	25.8	74.5	104.8	72.8	284.3
P=0.05	NS	Sig *	Sig **	Sig ***	Sig ***	Sig **	Sig ***
SE±	-	0.8	1.3	3.2	5.9	4.4	11.7
CD	-	1.8	2.8	7.1	12.9	9.6	25.7
2012-13							
T_0	0.4	3.4	27.0	63.0	74.0	52.0	219.8

Treatments	Leaf Area Duration (day)						
	20 D	40	60	80	100	120	Total
T_1	0.4	4.2	28.8	74.0	96.0	65.2	268.4
T_2	0.5	4.6	34.1	84.0	108.0	74.6	304.2
T_3	0.4	4.8	36.4	89.0	110.0	78.2	318.6
Mean	0.4	4.3	31.6	77.5	96.8	67.3	278.0
Sig	NS	Sig***	Sig ***	Sig ***	Sig ***	Sig ***	Sig ***
SE±	-	0.4	2.1	5.1	7.7	6.3	13.6
CD	-	1.0	4.7	11.2	17.0	13.9	30.0

Two years average total LAD was 222.6 in T_0, 269.3 in T1, 309.3 in T_2 and 323.4 in T_4. Observations revealed that the enrichment of CO_2 in wheat substantially increased the leaf area duration it may be attributed to delaying the rate of canopy senescence (Li *et al.* 2007).

4.5 Yield and yield attributes

Grain yield and its attributing factors are presented in this section.

4.5.1 Grain Yield

The observations on grain yield, straw yield, biological yield, HI, % effective tiller, number of grains spike^{-1}, grain weight plant^{-1} and grain test weight are presented in Table 4.5. The average wheat grain yield ('00 kg ha^{-1}) observed during 2011-12 and 2012-13 was 57.2 and 52.0 respectively. The difference in yield may be attributed to difference in weather conditions. If one looks at the rainfall received during the growing period in both 2011-12 and 2012-13, it is revealed that the winter rainfall during 2012-13 is comparatively high (261.8 mm) in comparison to the year 2011-12 (49.4 mm), mostly received in the anthesis period (6th and 7th weeks).

Table 4.5: Yield and yield attributes of Wheat *cv*. PBW 343 as affected by periodical CO_2 enrichment.

Treatments	Grain yield ('00 kg ha^{-1})	Straw yield ('00 kg ha^{-1})	Biological yield ('00 kg ha^{-1})	HI	% Effective tiller	No. of grain spike^{-1}	Grain weight plant^{-1} (g)	Test weight (g)
2011-12								
T_0	48.7	73.4	122.1	0.40	98.8	50.1	15.2	40.5
T_1	52.0	78.5	130.5	0.40	92.5	49.1	16.2	41.4
T_2	62.5	99.5	162.0	0.39	91.8	54.4	19.5	42
T_3	65.7	103.8	169.4	0.39	90.0	56	20.5	42.3
Mean	57.2	88.8	146.0	0.39	93.3	52.4	17.9	41.6
P=0.05	Sig**	Sig**	Sig**	Sig*	Sig*	Sig *	Sig *	NS
SE±	3.7	6.3	9.9	0.34	2.3	2.8	1.1	-
CD	8.1	13.8	21.8	0.76	1.1	3.8	2.5	-
2012-13								

Treatments	Grain yield ('00 kg ha^{-1})	Straw yield ('00 kg ha^{-1})	Biological yield ('00 kg ha^{-1})	HI	% Effective tiller	No. of grain $spike^{-1}$	Grain weight $plant^{-1}$ (g)	Test weight (g)
T_0	45.7	67.1	112.8	0.41	94.4	45.9	14.3	39.5
T_1	48.4	71.0	119.4	0.41	91.2	45.7	15.1	39.6
T_2	55.7	82.6	138.3	0.40	89.9	47.2	17.4	40.5
T_3	58.3	86.1	144.4	0.40	89.3	46.4	18.2	41.1
Mean	52.0	76.7	128.7	0.40	91.2	46.3	16.2	40.2
Sig	Sig**	Sig**	Sig**	NS	Sig*	NS	Sig **	Sig *
SE±	2.6	3.8	5.6	-	0.3		0.81	1.2
CD	5.7	8.5	12.4	-	0.7		1.7	0.56

Since this is the most sensitive stage for wheat crop, any abnormality (here excess moisture) leads to reduction in yield. Further, grain yield was significantly affected by CO_2 enrichment of the crop. The grain yield recorded in different CO_2 treatments was significantly differs in both the year. During 2011-12 the average grain yield ('00 kg ha^{-1}) was 57.2 whereas; during 2012-13 it was decreased and recorded as 52.0. Two years' average grain yield ('00 $kgha^{-1}$) in different treatments was recorded as 47.2 in T_0, 50.2 in T_1, 59.1 in T_2 and 62.0 in T_3 indicating a direct correlation with CO_2 enrichment. The two years average increase in grain yield by CO_2 enrichment treatments (T_1-T_3) over the control (T_0) was recorded as 34.9%. Increase in grain yield is attributable to increased grain number and grain test weight. Up to 60% increase in grain yield has been reported (Dahal *et al*., 2014) due to CO_2 enrichment. Increased grain yield by CO_2 enrichment treatment has also been reported (Deepak & Agrawal, 1999, Wu *et al.* 2004, Kimball 2002, Long *et al*., 2006, Uprety *et al.* 2009).

4.5.2 Straw Yield

Data pertaining to straw yield ('00 kg ha-^{1}) is presented in Table 4.5. Observations of the two year were consistent. Data revealed that during both the year, the yield was improved with CO_2 treatment. The average straw yield ('00 kg ha-^{1}) recorded was 88.8 and 76.7 respectively during the year 2011-12 and 2012-13. Average straw yield ('00 kg ha-^{1}) of two years under different treatments was recorded as 70.3 in T_0, 74.8 in T_1, 91.1 in T_2 and 95.0 in T_3. Increased straw yield with periodical CO_2 application is encouraging response. It may be attributed to assimilation of photosynthates resulting with increased number of leaves; leaf area and tiller count (Mishra *et al.,* 2013). This is in agreement with results from previous studies (Dahal *et al.*, 2014, Högy *et al.*, 2009b, Hogy *et al.*, 2010)

4.5.3 Biological yield

Total biological yield ('00 kg ha-[1]) which is the sum of straw yield and grain yield data is presented in Table 4.5. Observations revealed the significant increase in biological yield was noticed by periodical CO_2 enrichment of wheat crop. The overall average biological yield ('00 kg ha-[1]) was 146.0 during 2011-12 and 128.7 during 2012-13. The two-year average treatment wise biological yield ('00 kg ha-[1]) was 117.5 in T_0, 125.0 in T_1, 150.2 in T_2 and 156.9 in T_3. These observations confirm the beneficial effect of CO_2 application on wheat crop. It may be attributed to higher carbon flux (Mulchi *et al.*, 1992) and increased growth and yield attributes due to CO_2 enrichment. Increased biomass productivity has already been reported (Dahal *et al.*2014 and Erda *et. al.*2005).

4.5.4 Harvest index

Data presented in **Table 4.5** shows that results of harvest index (HI) was not consistent. Application of CO_2 recorded marginal reduction in HI during 2011-12 but remained unchanged during 2012-13. Reduction in HI due to CO_2 enrichment has been reported (Högy *et al.*, 2009b, Aranjuelo *et al.*, 2013).

4.5.5 % Effective tillers

Data pertaining to number of effective tiller or ear bearing tiller plant^{-1}as affected by different levels of CO_2 treatments is presented in **Table 4.5**. Overall average effective tiller recorded was 93.3 % during 2011-12 and 91.2% during 2012-13. The two year average treatment wise effective tiller was 96.6% in T_0, 91.8% in T_1, 90.9% in T_2 and 89.7% in T_3. Reduction in effective tiller under elevated CO_2 condition was also reported by Högy *et al.*, (2013).

4.5.6 Number of grain per spike

Data regarding the number of grains per spike was affected by different levels of CO_2 treatments is presented in **Table 4.5**.Overall average number of grains per spike recorded was 52.4 during 2011-12 and 46.3 during 2012-13. The two year average treatment wise grains per spike was 48.0 in T_0, 47.4 in T_1, 50.8 in T_2 and 51.2 in T_3. Increase in number of grain might be attributed to enhanced rate of photosynthesis which provides increased photo assimilate for grain development. Increased number of grains per spike due to CO_2 enrichment has been reported (Xiao *et al.*, 2009, Högy *et al.*, 2009a).

4.5.7 Grain weight per plant (g)

Grain weight per plant affected by different levels of CO_2 treatments is presented in Table 4.5 Overall average grains weight per plant was recorded as 17.9 g during 2011-12 and 16.2 g during 2012-13. The two year average treatment wise grain weight per plant was 14.8 g in T_0, 15.7 g in T_1, 18.5 g in T_2 and 19.4 g in T_3. Increased number of grains could be attributed to the increased number of spikelet per earhead in CO_2 enrichment treatment. Increased number of grains per spike has been reported (Batts *et al.*, 1998; Hogy *et al.*, 2010; Högy *et al.*, 2013)

4.5.8 Test weight (g)

The grain test weight affected by different levels of CO_2 treatments is presented in Table 4.5. Overall average grains test weight recorded was 41.6 g during 2011-12 and 40.2 g during 2012-13. The two year average treatment wise grain test weight was 40.0 g in T_0, 40.5 g in T_1, 41.3g in T_2 and 41.7g in T_3. Increase in grain test weight with CO_2 enrichment was not significant. Results are in agreement with the findings reported earlier (Uprety *et al.*, 2009; Xiao, *et al.*, 2009).

4.6 Physical Quality of Grain

Physical quality of wheat grain was judged with its length (mm), width (mm) and width wise % grain size distribution is presented in Table 4.6.The average length of grain was recorded as 7.0 mm during 2011-12 and 7.5 mm during 2012-13. Similarly the average width of grain recorded was 3.1 mm during 2011-12 and 3.7 mm during 2012-13. Overall reduced grain size was noticed during 2011-12 but the treatment effect was non-significant for length and width of grain. Similar results were also reported by Hogy *et al.* (2009a).

Table 4.6: Physical quality of grain of wheat *cv*. PBW 343 as affected by periodical CO_2 application.

Treatments	Length of grain (mm)		Width of grain (mm)		Width wise % distribution of grain size					
					>3mm		3-2.5mm		< 2.5mm	
	2011-12	2012-13	2011-12	2012-13	2011-12	2012-13	2011-12	2012-13	2011-12	2012-13
T_0	6.5	7.0	2.7	3.4	36.7	50.0	26.7	20.0	36.7	30.0
T_1	7.1	7.7	3.1	3.7	36.7	46.7	36.7	33.3	26.7	20.0
T_2	7.3	7.6	3.4	3.7	43.3	56.7	36.0	26.7	22.7	16.7
T_3	7.3	7.8	3.4	3.9	43.3	46.7	30.0	33.3	26.7	20.0
Mean	7.0	7.5	3.1	3.7	40.0	50.0	32.3	28.3	28.2	21.7
Sig	NS	NS	Sig*	NS	NS	NS	NS	NS	Sig*	NS
SE±	-	-	0.2	-	-	-	-	-	5.0	-
CD	-	-	0.4	-	-	-	-	-	11.0	-

4.7 Chemical Quality of Grain

4.7.1 Grain protein and carbohydrate

Biochemical qualities such as protein and carbohydrate content (%) as affected by various CO_2 levels is presented in Table 4.7. Grain protein content (%) was significantly reduced by increasing the CO_2treatment levels. Average protein content recorded was 10.1% and 10.7% during 2011-12 & 2012-13 respectively. Two year mean protein content in descending order was recorded as 11.6 % in T_0, 10.8 % in T_1, 10.1 % in T_2 and 10.0 % in T_3. Decrease in protein content may be attributed to decreasing grain nitrogen content. Decreased Protein content in the grain under elevated CO_2 has been reported in previous studies (Högy *et al.* 2009a; Högy *et al.* 2009b; Högy *et al.* 2013).

Table 4.7.1: Chemical quality of grain of wheat *cv*. PBW 343 as affected by periodical CO_2 application.

Treatments	Protein content (%)	Total carbohydrate (%)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)
	2011-12							
T_0	10.6	64.6	1.98	0.44	0.68	0.03	0.11	0.13
T_1	10.1	65.1	1.86	0.41	0.61	0.03	0.12	0.14
T_2	9.9	67.4	1.77	0.4	0.63	0.03	0.14	0.14
T_3	9.8	71.5	1.75	0.41	0.65	0.03	0.14	0.14
Mean	10.1	67.1	1.84	0.42	0.64	0.03	0.13	0.14
Sig	Sig *	Sig *	Sig *	NS	NS	NS	Sig *	NS
SE±	0.21	1.6	0.07	-	-	-	0.01	-
CD	0.53	2.2	0.16	-	-	-	0.03	-
	2012-13							
T_0	11.6	61.61	2.04	0.48	0.87	0.04	0.15	0.16
T_1	10.9	61.71	1.93	0.46	0.74	0.02	0.14	0.17
T_2	10.2	65.72	1.8	0.46	0.8	0.03	0.18	0.17
T_3	10.1	67.28	1.77	0.46	0.78	0.03	0.2	0.16
Mean	10.7	64.1	1.88	0.47	0.8	0.03	0.17	0.16
Sig	Sig **	Sig *	Sig *	NS	NS	NS	NS	NS
SE±	0.37	1.1	0.07	-	-	-	-	-
CD	0.83	3.2	0.15	-	-	-	-	-

Total carbohydrate content (%) increased significantly by each CO_2 application. Average total carbohydrate content recorded was 67.1 % and 64.1% during 2011-12 & 2012-13 respectively. The two year average carbohydrate content was recorded as 63.1 %, 63.4 %, 66.6 % and 69.4 % under T_0, T_1, T_2 and T_3respectively. The increase in carbohydrate content at elevated CO_2 levels could be attributed to increased assimilation of photosynthates. Increased carbohydrate content in wheat grain has already been reported (Tester *et al.* 1995; Hogy *et al.*, 2008; Mishra *et al.*, 2013).

4.7.2 Grain mineral nutrients

Data pertaining to grain macro nutrient content such as N, P, K, Ca, Mg, and S for the year 2011-12 and 2012-13 is presented in Table 4.7. Macronutrients except N and Mg present in the grain seems to be unaffected by periodical application of CO_2. Average N_2 content was recorded as 1.84 % in 2011-12 and 1.88% in 2012-13. Decreased nitrogen content due to CO_2 enrichment in grain might be attributed to dilution of nutrients due to accumulation of non-structural carbohydrates. Accumulation of more C reduces the proportion of other major nutrients. Decreased nitrogen content due to CO_2 enrichment in grain has already been reported (Dietterich *et al.*, 2015, Usui *et al.*, 2015, Fernando *et al.*, 2014a).

Chapter –5

DSSAT MODEL CALIBRATION AND EVALUATION

This chapter describes the techniques employed in the calibration and evaluation of the DSSAT CERES Wheat model using field experimental results of the study "Effect of Periodical CO_2 Application on Growth, Development and quality of Wheat crop" conducted during 2011-12 and 2012-13.

5.1 DSSAT CERES-Wheat Model

The Decision Support System For Agrotechnology Transfer (DSSAT) was originally developed by an international network of scientists, cooperating in the International Benchmark Sites Network for Agrotechnology Transfer project to facilitate the application of crop models in a systems approach to agronomic research. It has the capability to simulate the crop growth, development and biomass production over the time as well as soil-water, carbon and nitrogen processes and management practices under dynamic environmental situation (Jones *et al.*, 2003; Hoogenboom *et al.*, 2004).

Model has separate module for wheat crop called CERES-Wheat (Ritchie and Otter, 1985). It simulates phasic development of the crop based on genetic coefficient of the cultivar, weather parameter, soil and crop management practices. It can also simulate plant growth, development, yield attributes and yield considering the effects of weather condition, management practice, genetics character, soil-water regime, Carbon and Nitrogen applications (Timsina, 2006; Singh *et al.,* 2010a). The model has the ability to simulate all these parameters based on different input modules like carbon balance, soil water balance (Ritchie and Otter, 1985) and nitrogen balance (Gijsman *et al*. 2002). The phenology of the wheat crop is simulated by the CERES-Wheat model based on the growing degree days (GDD) and modified to suite under all growing conditions (Alocilja and Ritchie, 1991). Biomass or dry matter production is simulated as a function of Photosynthetically Active Radiation (PAR) and Radiation Use Efficiency (RUE) of crops. The model predicts daily photosynthesis using RUE approach as a function of daily irradiance for a full canopy, which is then multiplied by a factor ranging from 0 to 1 for light interception, temperature, leaf nitrogen and water status (Amiri, *et al*., 2013). CERES Wheat model adapts Beer's Law to simulate the amount of light absorbed by the crop during the process of photosynthesis (Yoshida, 1981).

This model computes daily changes in root zone soil-water content by using the soil infiltration rate, drainage coefficient and Evapotranspiration (ET) of crops (Ritchie, 1972). The water balance subroutine calculates run-off by the modified United States Department of Agriculture (USDA)-Soil and Conservation Service (SCS) curve number method (Williams, 1990). The CERES model uses various weather data, *i.e.* daily solar radiation, minimum and maximum air temperature and daily total precipitation to calculate ET using Priestley-Taylor equation.

DSSAT model has been extensively used for yield gap analysis, decision making and planning, strategic and tactical management decisions, climate change impact studies (Batchelor *et al.* 2004; Ahuja *et al.* 2014). In India, several studies have demonstrated the utility of DSSAT for impact assessment of climatic change (Saseendran *et al.*, 2000; Attri *et al.*, 2011; Rana *et al.*, 2011; Rana *et al.*, 2014a; Behera *et al.,* 2015, Mall *et al.,* 2016). It has different sub modules to generate various files *viz.* weatherman for weather files, S Build for soil files, X Build for crop management and AT for genetic coefficient. Various input files required in a simulation are described below:

5.2 DSSAT Input Files

5.2.1 Soil file

The model has a unique module named as S Build to generate soil file by entering layer wise soil information. The minimum input datasets required for generating soil files are the location details, soil color, slope etc. and layer wise details of silt (%) and clay (%), and nitrogen , pH, organic carbon (OC) and cation exchange capacity (CEC) *etc*. The data generated in the soil file using S Build is bulk density (BD), saturation point (SP), field capacity (FC), permanent wilting point (PWP), runoff curve number (RO), albedo fraction (Alb), Evaporation limit (EL) and Drainage rate (DR) etc. Land features and layer wise soil profile data of physico chemical properties (Table 4.1) were used for developing soil file.

The soil of Roorkee region is sandy loam in texture which is brown in color with an albedo fraction of 0.13. The drainage rate of soils was 0.4 mm/day with the 73 runoff curve number. The soils were classified into order Inceptisols. Roorkee soils were characterized by 12-16% clay content, 24-40% silt with 0.6% OC in the topsoil, and therefore they were classified into sandy loam type of soils. PWP ranged between 0.097 – 0.121 $cm^3\ cm^{-3}$, FC ranged between 0.2 -0.224 $cm^3\ cm^{-3}$ and saturation point (SP) 0.3 – 0.4 $cm^3\ cm^{-3}$. BD of the soil ranged between 1.54 g cm^{-3} in the top layers to 1.42 g cm^{-3} in the subsoil layers. CEC also ranged between 13-15 cmol kg^{-1} in various layers of the soil.

Beside this, model automatically generate saturated water content (SAT), soil root growth factor (SRGF), soil drained lower limit (LL) and soil drained upper limit (DUL) to calculate water balance.

5.2.2 Weather file

WeatherMan module of DSSAT with daily input of weather data converts or generates daily DSSAT compatible weather file. The minimum datasets required by the weatherman are weather station location details *viz*. name, climate class, latitude, longitude and elevation (above msl), and anemometer height (m from the ground) as well as daily observations of rainfall (mm), maximum temperature, minimum temperature (ºC) and solar radiation (MJ m^{-2} day). A weather file generated for the experimental period (2011-12, 2012-13 and 2013-14) are presented in Annexure 1.

5.2.3 Genetic coefficient file

Genetic coefficients were generated by creating the file A and file T in Experimental Data Editing Program (AT Create). In this process the observed data for at least six crop growth and development parameters with four dates of sowing is required to calibrate the coefficient. Genetic coefficients of a cultivar whose growth pattern resembles to the test cultivars, which is preexists within the model was selected for modification by running DSSAT model using actual soil, weather and crop management data and make it usable by adjusting various coefficients through iterative process till the observed and simulated crop parameter data matched for wheat *cv*. PBW 343. The WHCER045.CUL file was opened and the genetic coefficients of wheat *cv*. PBW 343 were incorporated into the DSSAT model.The values of genetic coefficient of wheat cultivars PBW 343 for the soil climatic conditions of Roorkee is given in Table 5.1. These coefficients determine the phenology and grain yield components of a particular variety as affected by other parameters such as weather, soil etc (Iglesias, 2006).

Table 5.1: Genetic coefficient of wheat variety PBW-343

Cultivars	P_1V	P_1D	P_5	G_1	G_2	G_3	PHINT
PBW-343	20	68	550	19	44	1.2	95

Where,

P_1V: Days at optimum vernalizing temperature required to complete vernalization;

P_1D:Percentage reduction in development rate in a photoperiod 10 hour shorter than the threshold relative to that at the threshold;

P_5:Grain filling (excluding lag) phase duration in degree days (°C.d);

G_1:Kernel number per unit canopy weight at anthesis (g);

G_2:Standard kernel size under optimum conditions (mg);

G_3:Standard, on-stressed dry weight (total, including grain) of a single tiller at maturity (g) and PHINT: Interval between successive leaf tip appearances (°C.d).

5.2.4 Crop management file

The X Build module of DSSAT generates crop management file. This module required input data of schedule of field operations *viz.* planting, irrigation, fertilizer application, harvesting etc. Details of DSSAT generated crop management file is presented in ***Annexure 2a and 2b***.

5.3 Generation of Genetic Coefficient

In order to calibrate and develop genetic coefficient of *cv.* PBW 343, field experiment with four dates of sowing [15th November (D_1); 22nd November (D_2); 29th November (D_3) and 6th December (D_4)] with a recommended package of practices were conducted at the Demonstration Farm of Indian Institute of Technology Roorkee during rabi 2013- 2014 under ongoing FASAL (Forecasting Agricultural output using Space, Agro-meteorology and Land based observations) scheme. Data pertaining to emergence (DAS), anthesis (DAS), maturity (DAS), product weight or grain weight (kg dm ha^{-1}), product unit weight or unit grain weight (g dm), product number or grain number (no m^{-2}), product number (no $group^{-1}$), product harvest index (ratio), maximum leaf area index, canopy (tops) wt (kg dm ha^{-1}) was taken from the experiment. Other data on growth, development, and yield attributes was also recorded. Data recorded from the experiment was inserted in to Experimental Data Editing Program, and model was executed using actual crop management, soil, weather data and genetic coefficient file of Indian cultivar which was preexist in the model. The model was run for each date of sowing, by adjusting various parameters of genetic coefficients through an iterative process till the values of simulated and actual parameters became statistically closer. The schedule of experimental field operations undertaken during the *Rabi* season of year 2013- 2014 are given in Table 5.2.

Table 5.2: Schedule of field operations conducted during *Rabi* 2013- 2014.

S.No.	Field operations	D_1	D_2	D_3	D_4
Experiment detail					
1	Replications	3			
2	Plot size	2m*2m			
3	Spacing (Row to Row)	20 cm			
4	Spacing (Plant to Plant)	15 cm			
5	Sowing depth	5 cm			
6	Method of sowing	Dibbling			
7	1st ploughing	27.10.2013	27.10.2013	27.10.2013	27.10.2013
8	Levelling	29.10.2013	29.10.2013	29.10.2013	29.10.2013
9	2nd ploughing	09.11.2013	09.11.2013	09.11.2013	09.11.2013
10	Layout	14.11.2013	21.11.2013	28.11.2013	05.12.2013
11	Sowing date	15.11.2013	22.11.2013	29.11.2013	06.12.2013
Irrigation					
12	Method of application	Flooding			
13	1st irrigation (50 mm)	06.12.2013	13.12.2013	21.12.2013	29.12.2013
14	2nd irrigation (50 mm)	14.01.2013	19.01.2013	25.01.2013	25.01.2013
15	3rd irrigation (50 mm)	06.03.2013	11.03.2013	15.03.2013	15.03.2013
16	4th irrigation (50 mm)	22.03.2013	26.03.2013	26.03.2013	26.03.2013
Fertilizer application					
17	Basal dressing (50:40:40)	15.11.2013	22.11.2013	29.11.2013	06.12.2013
18	1st top dressing (25:0:0)	08.12.2013	14.12.2013	22.12.2013	30.12.2013
19	2nd top dressing (25:0:0)	15.01.2013	20.01.2013	26.01.2013	26.01.2013
20	Weeding	As and when required			
21	Harvesting	05.04.2014	08.04.2014	09.04.2014	10.04.2014
22	Threshing	06.04.2014	09.04.2014	10.04.2014	11.04.2014

5.4 Statistical Analysis

Simulated and actual values were statistically tested using various statistical procedure *i.e.* percent deviation, RMSE (Fox, 1981), NMSE (Kumar, 2000), MBE (Addiscott and Whitmore, 1987), d (Willmott and Wicks, 1980), FB (Kumar, 2000) and CD (Loague and Green, 1991). They are described in forthcoming paragraphs.

5.4.1 Percent deviation (Dev %)

Deviation is a measure of difference between the observed value and simulated or estimated value of a variable, expressed in terms of percentage. Percent deviation within ± 10% is statistically acceptable. This is calculated using the formula as given below:

$$\text{Dev}\% = \frac{\text{Sim} - \text{Obs}}{\text{Obs}} * 100 \quad \text{...} \mathbf{(5.1)}$$

5.4.2 Root mean squared error (RMSE)

The Root Mean Square Error (RMSE) (also called the root mean square deviation, RMSD) is a frequently used measure of difference between values predicted by a model and the values actually observed. These individual differences are also called residuals, and the RMSE serves to aggregate them into a single measure of predictive power.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(Sim_i - Obs_i\right)^2}{n}} \quad \text{……………………… ……………………… (5.2)}$$

RMSE value closure to zero is considered to be optimal.

5.4.3 Normalized root mean square error (NRMSE)

NRMSE emphasizes the scatter in the entire dataset. The normalization by the product assures that the NRMSE will not be biased towards models that over predict or under predict. Smaller values of NRMSE denote better model performance. The Normalized Root Mean Square Error (NRMSE) is used to estimate the deviation of forecasted value from the observed value. The Normalized Root Mean Square Error is dimensionless and calculated using the following formula.

$$NRMSE = \frac{1}{N}\frac{\sum_{i=1}^{n}(Sim - Obs)^2}{\sum_{i}^{n}(Sim * Obs)} \quad \text{……………………………………… (5.3)}$$

NRMSE value closure to zero is considered to be optimal.

5.4.4 Mean bias error (MBE)

This is a difference between predicted and observed value. It can result either + or -. Being 0 is the optimal. This is calculated as follows:

$$MBE = \sum_{i=1}^{n}\frac{Sim_i - Obs_i}{n} \quad \text{……………………………………… (5.4)}$$

5.4.5 Fractional bias (FB)

It is similar to mean bias but it is normalized to make it dimensionless. FB varies between +2 to -2 with an ideal value of zero for an ideal model. Ideal value of Fractional Bias (FB) is zero but is practically not possible therefore acceptable limits are fixed. This is calculated as follows:

$$FB = 2 * \left(\frac{Sim - Obs}{Sim + Obs} \right) \qquad \text{......... (5.5)}$$

5.4.6 Index of agreement (d)

The index of agreement can detect additive and proportional differences in the observed and simulated means and variances however, it is overly sensitive to extreme values due to the squared differences (Legates and McCabe, 1999).The index of agreement (d) developed by Willmott (1981) as a standardized measure of the degree of model prediction error and varies between 0 and 1. A value of 1 indicates a perfect match, and 0 indicates no agreement at all. This is calculated as follows:

$$d = 1 - \frac{\sum_{i=1}^{n} (Sim_i - Obs_i)^2}{\sum_{i=1}^{n} (|Sim_i - \overline{Obs}| + |Obs_i - \overline{Obs}|)^2} \qquad \text{......... (5.6)}$$

Where,

N = number of observations; Sim = CERES-Wheat simulated value and Obs = Observed value

5.4.7 Coefficient of determination (CD)

CD is the proportion of total variance of measurements explained by the estimates but it is not the same as r^2. CD value ≥ 1 is the best that is the deviation from the mean of measurements is the same for simulated and observed. This is calculated as follows:

$$CD = \frac{\sum_{i=1}^{n} (Sim_i - \overline{Obs})^2}{\sum_{i=1}^{n} (Obs_i - \overline{Obs})^2} \qquad \text{......... (5.7)}$$

5.5 Model Calibration

In order to calibrate the model for soil climatic conditions of Roorkee a field trial were conducted by growing wheat crop *cv*. PBW 343 on four dates of sowing (Nov.15; Nov.22; Nov.29 and Dec. 06) during *Rabi* 2013-14 at the demonstration farm of the Indian Institute of Technology Roorkee. Simulated and observed results of ten parameters (days taken to emergence, days taken to anthesis, days taken to maturity, grain yield (kg/ha), Unit grain weight (g), grains (numbers/m^2), grains (numbers/earhead), harvest index, leaf area index (maximum), effective tillers (numbers/m^2), total biomass (kg/ha) and straw yield (kg/ha) along with the statistical tests are presented in table 5.3 and detailed model output is presented in Annexure 3. Seven statistical tests were performed to test the acceptability of result. With exception of a few crop parameters, majority of parameters shows insignificant difference between simulated and observed results. In view of this, the DSSAT CERES-

Wheat model for the present soil climatic condition is accepted as calibrated. Similar type of model calibration studies using different cultivars has already been reported (Challinor *et al*., 2004; Sudhishri and Dass, 2006; Pal *et al*., 2010; Pal *et al*., 2012a; Pal *et al*., 2015a, Zhang *et al*., 2013; Meena *et al.* 2015; Mall *et al.* 2016).

5.6 Model Evaluation

Calibrated model was used to evaluate the study of periodical application of the CO_2 effect on the growth and development of wheat *cv*. PBW 343 conducted during 2011-12 and 2012-13. Actual soil data, weather condition, crop management practices and CO_2 applications (schedule and concentration) recorded from the experimental study, were incorporated in the model. The effect of CO_2 application at periodical interval on growth, yield and yield parameters was simulated. The results obtained were compared with the observed data to test the validity of simulated output.

The details of field experiment with four CO_2 treatments (T_0, T_1, T_2 and T_3) conducted in two consecutive years and observation recorded are presented in *chapter IV and annexure 5*. Simulated result of growth, development, yield, yield attributes and grain quality parameters *viz.*emergence (DAS), anthesis (DAS), maturity (DAS), grain yield (kg/ha), test weight (g), grain number (m^2), grain number /ear, HI % , max LAI, total biomass (kg/ha) straw yield (kg/ha) grain N_2 content (%) of wheat *cv*. PBW 343 under various CO_2 levels for the year 2011-12 and 2012-13 alongwith the simulated *vs*. observed statistics are presented in Table 5.4. In order to evaluate the results, seven statistical tests *viz*. % deviation, r^2, RMSE, NMSE, MBE, d, FB and CD were applied. All the statistical tests approved the validity of simulated results to that of the experimentally observed results.

Simulated results revealed that days taken to express the phenological stages were reduced with CO_2 application in both the years as compared to control. Grain yield (kg/ha) increased linearly with increasing the frequency of CO_2 application. Similarly, grain test weight (g), grain numbers/ m^2, grains /earhead, maximum leaf area index, total biomass (kg/ha), straw yield (kg/ha) and nitrogen content in grain was also increased with increasing the frequency of CO_2 application in both the years.

Table 5.3: Calibration of DSSAT CERES-Wheat model for wheat *cv* PBW 343 sown on different dates during *Rabi* 2013-14.

VARIABLE (sowing dates & statistical test)		Emergence (DAS)	Anthesis (DAS)	Maturity (DAS)	Product wt (kg dm ha^{-1})	Product unit weight (g dm)	Product number (no m^{-2})	Product number (no group^{-1})	Product harvest index (ratio)	Maximum leaf area index	Final shoot number (m^{-2})	Canopy (tops) wt (kg dm ha^{-1})	Vegetative wt (kg dm ha^{-1})
		Observations											
15.11.2013	**Simulated**	6	98	148	4774	0.045	10608	29.4	0.44	2.8	361	10900	6126
	Observed	7	95	142	4834	0.043	11143	31.9	0.43	4.1	349	11277	6443
22.11.2013	**Simulated**	6	98	144	4728	0.045	10506	29	0.43	2.9	362	11082	6354
	Observed	6	94	138	4576	0.043	10643	30.8	0.42	3.8	346	11001	6425
29.11.2013	**Simulated**	7	96	139	4151	0.045	9225	27.2	0.42	2.7	339	9964	5813
	Observed	8	92	132	3979	0.041	9705	27.1	0.42	3.4	358	9388	5409
06.12.2013	**Simulated**	7	95	128	3508	0.04	8769	29	0.39	2.2	302	8987	5479
	Observed	8	92	126	3422	0.041	8347	26.8	0.4	3.1	311	8601	5179
% Dev		-9.8	3.8	3.3	2.2	4.2	-1.5	-1.3	0.32	-26.3	0	2	1.8
RMSE		0.9	3.5	5.5	125.9	0	422.3	1.9	0	1	14.7	396.6	299.5
NMSE		0.016	0.001	0.002	0.001	0.003	0.002	0.004	0.001	0.099	0.002	0.002	0.003
MBE		-0.8	3.5	4.5	87	0	-182.5	-0.5	0	-1	0.2	166	79
d		0.7	0.5	0.7	1	0.6	0.9	0.6	0.9	0.5	0.9	1	0.9
FB		-0.11	0.04	0.03	0.02	0.04	-0.02	-0.02	0	-0.3	0	0.02	0.01
CD		1.2	8.3	3.5	0.9	7.8	0.6	0.2	2.3	6.7	1.9	0.6	0.3

Where, '% Dev' is Percent Deviation; 'RMSE' is Root Mean Square Error; 'NMSE' is Normalized Root Mean Square Error; 'MBE' is Mean Bias Error; 'd' is Index of Agreement; 'FB' is Fractional Bias and 'CD' is Coefficient of determination.

Table 5.4: Evaluation of DSSAT CERES-Wheat model for wheat *cv* PBW 343 field experimented during *Rabi* 2011-12 & 2012-13

Parameters	**2011-12***				**2012-13***				**#Simulated vs. Observed statistics**						
	T0	**T1**	**T2**	**T3**	**T0**	**T1**	**T2**	**T3**	r^2	**RMSE**	**NMSE**	**MBE**	**d**	**FB**	**CD**
Emergence (DAS)	8	8	7	9	7	6	7	8	0.42	0.9	0.017	0.6	0.7	0.09	1.9
Anthesis (DAS)	98	95	97	94	102	99	98	98	0.74	4.1	0.002	3.9	0.6	0.04	3.4
Maturity (DAS)	139	139	132	133	141	138	139	139	0.72	2.9	0.001	2.0	0.6	0.01	8.7
Grain yield ($kgha^{-1}$)	5166	5361	6008	6791	4666	4970	5684	5900	0.95	184.2	0.001	107.9	1.0	0.02	0.9
Test weight (g)	40	40	43	41	39	39	41	42	0.57	3.9	0.002	3.7	0.4	0.04	4.9
Grain number m^{-2})	12914	13402	13973	16564	11963	12744	13863	14048	0.80	697.8	0.003	342.6	0.9	0.03	0.9
Grain number ear^{-1}	36.8	41.2	49.7	47.2	36	38	41.2	40.3	0.69	8.4	0.035	-8.1	0.5	-0.18	6.3
HI %	41	39	39	39	44	42	41	39	0.51	1.5	0.002	0.7	0.6	0.02	7.0
Max LAI	3.4	3.3	3.5	3.6	3.4	3.8	3.6	3.6	0.06		-	-	-	-	-
Total Biomass (kg ha^{-1})	12728	13754	15509	17635	10592	11951	13707	14958	0.93	556.9	0.002	118.0	1.0	0.01	1.2
Straw yield (kg ha^{-1})	7562	8393	9501	10844	5926	6981	8023	9058	0.91	453.3	0.003	11.0	1.0	0.00	1.3
Grain N_2 content (%)	1.6	1.5	1.5	1.4	1.7	1.6	1.5	1.4	0.89	0.3	0.040	-0.3	0.4	-0.20	1.8

** Simulated result for the year 2011 and 2012*

 # Statistical result: comparison of simulated and observed data. (Observed data presented in Chapter-IV)

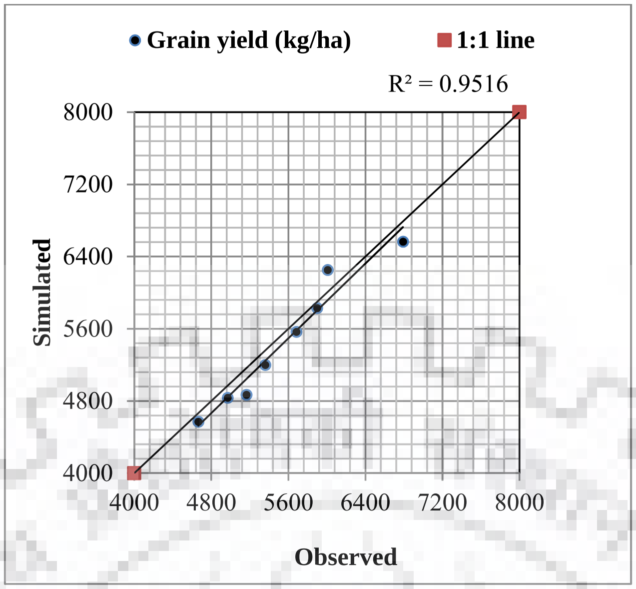


Figure 5a: Simulated *vs.* observed grain yield (kg ha^{-1})

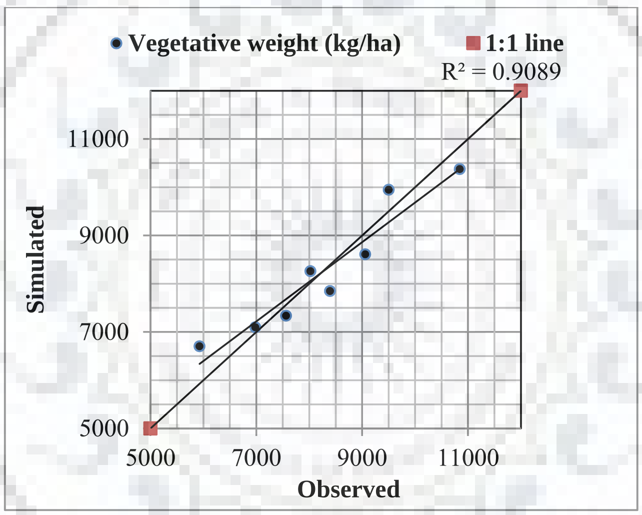


Figure 5b: Simulated *vs.* observed vegetative yield (kg ha^{-1})

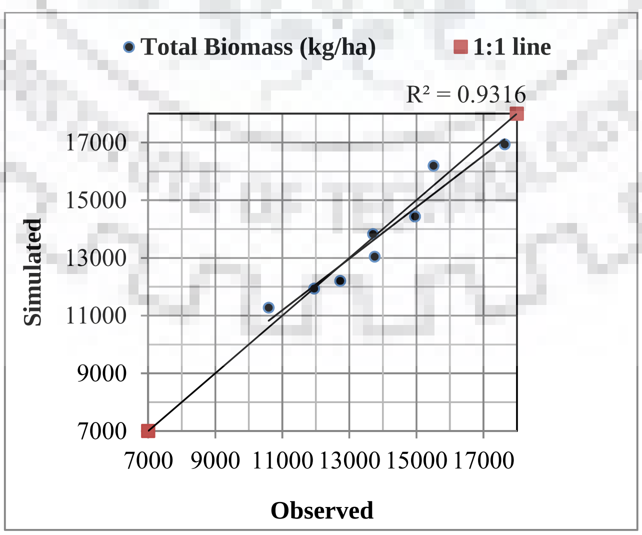


Figure 5c: Simulated *vs.* observed total biomass (kg ha^{-1})

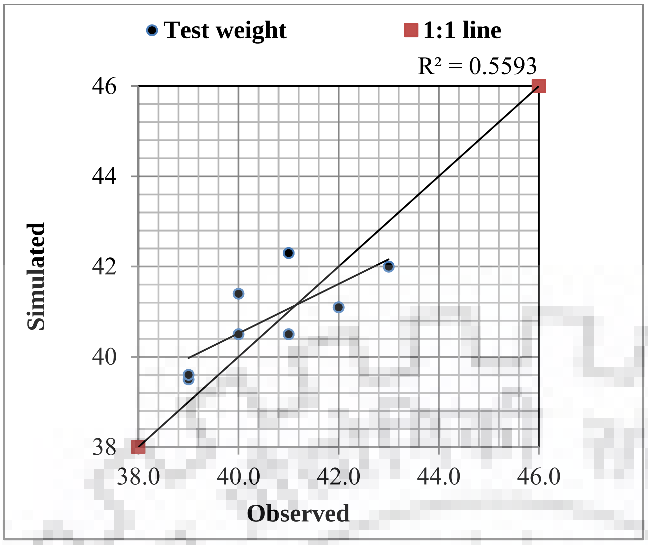


Figure 5d: Simulated *vs.* observed test weight (g)

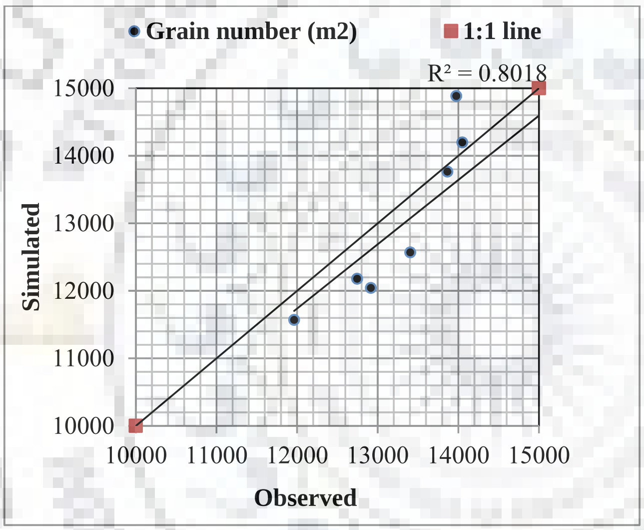


Figure 5e: Simulated *vs.* observed grain number (m^{-2})

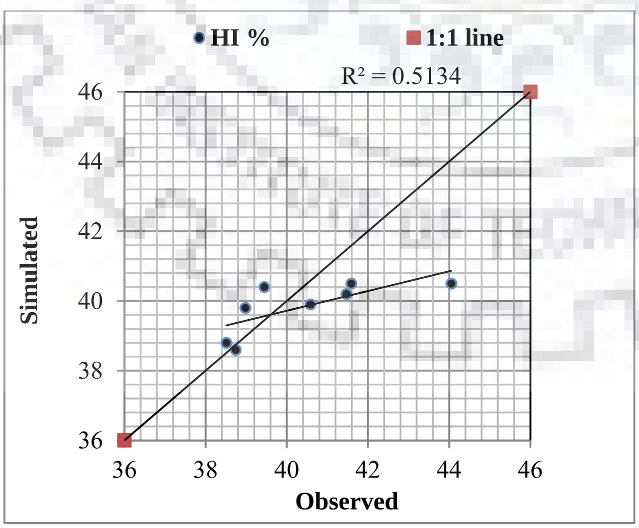


Figure 5f: Simulated vs. observed Harvest Index (%)

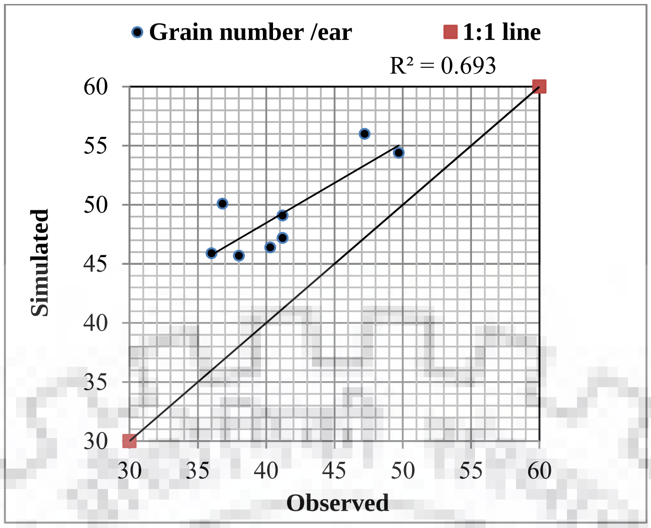


Figure 5g: Simulated *vs.* observed grain number year^{-1}

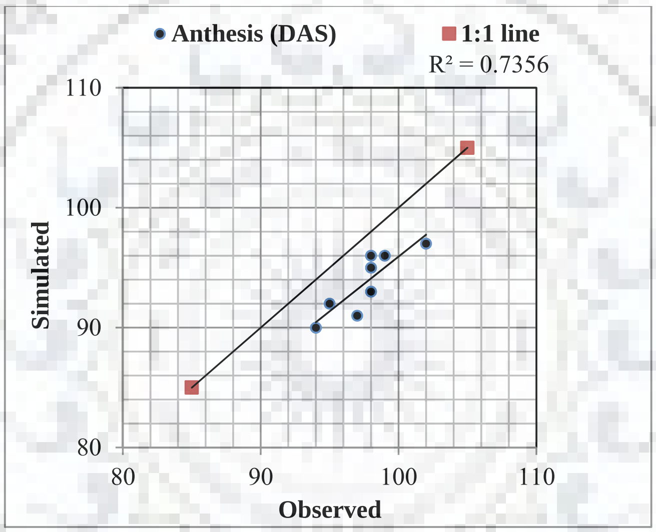


Figure 5h: Simulated *vs.* observed anthesis days (DAS)

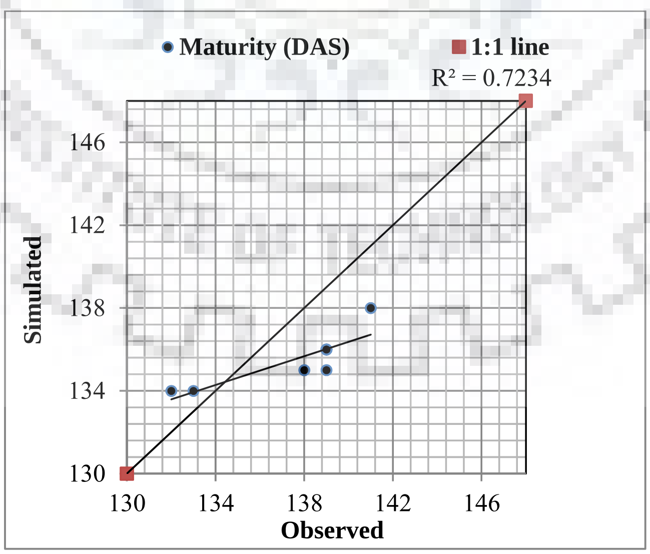


Figure 5i: Simulated *vs.* observed maturity days (DAS)

Harvest index, however decreased with increasing the frequency of CO_2 application. Scatter diagram presented at Figure 5 a-i demonstrated a perfect match between the observed and simulated results of grain yield, vegetative yield, total biomass, test weight, grain number, harvest index, grain number, anthesis days and maturity days. Simulated and observed values of grain yield, vegetative yield, total biomass, test weight, grain number, harvest index, grain number, anthesis days and maturity days statistically matched (Table 5.4). Simulation *vs* Observed results depicted in figure 5a-5i revealed that the evaluated model can be utilized as a supportive tool to analyse the impact of elevated CO_2 on wheat grain yield grown in the agroclimatic conditions of Haridwar district located in Indo-gangatic plains. Results on the similar lines have also been reported (Tripathi *et al*., 2014; Khichar *et al*., 2008).

Chapter –6

AGRONOMIC APPROACHES UNDER CLIMATE CHANGE

This chapter describes the agronomic ways to improve the productivity of wheat under changing climate period of 2015-2030.

6.1 Overview

It has been reconfirmed from the Fifth Assessment Report of the Inter-Governmental Panel on Climate Change (IPCC-AR5) that the global atmospheric concentrations of greenhouse gases (GHGs), specially CO_2 have increased significantly since mid-18th century due to anthropogenic cause. Ever increasing concentrations of GHGs may lead abrupt changes in global climate which will affect the every facet of agriculture such as crop production, livestock, soil etc. (Myers *et al*., 2014). Various reports published related to impact of climate change on crop clearly indicates that by doubling the CO_2 level rate of photosynthesis may increase by 24-43% depending on the environment and crop (Kimball 1983). Application of 550 ppm CO_2 in open field condition under FACE environment leads to enhance the yield of wheat and rice up to 8- 10%, soybean up to 15%, whereas no significant effect was noticed on maize and sorghum (Biernath *et al.*, 2013; Long *et al.* 2005, Sultana *et al*. 2009). If the effect of elevated CO_2 neglected the productivity of rice, maize, canola, wheat potato may decreased by 3-12% in China (Chavas *et al.*, 2009). Studies carried out in India indicates that the loss of 4-5 MT in wheat production likely to occurs by every rise of 1^{o}C temperature this increase in temperature over Indian continent would around coincide with 2020-2030 period (Aggarwal *et al.*, 2008). Over all climate are supposed to be major drivers of future crop production besides other parameters like soil and water status.

It is clear from the reports of various researches that elevated CO_2 will promote the growth and productivity of C_3 plants, but increase in temperature resulting from increased GHGs may lead to decline the production in many ways *i.e.* by shorten crop duration, by increasing the rates of respiration and evapotranspiration, by accelerating nutrient mineralization and by reducing nutrient use efficiencies and supporting the outbreaks of insect pest and diseases. Moreover variability in rainfall intensity and distribution may cause drought and flood problem. The situation is dangerous for India where more than 60 percent populations rely on agriculture or agriculture based industries. Abrupt changes in climate and burgeoning population are likely to further increase the pressure on Indian agriculture hence the food grain requirement likely to be doubled by 2030 (Paroda and Kumar, 2000).

Adaptation and mitigation measures in agriculture are the approaches to deal with the future climate change scenario. Mitigation has its own problem in the era of globalization and development, therefore adaptation is likely to be a possible means of sustaining productivity (Brassard and Singh 2008; Choudhary *et al.*, 2014, White *et al.*, 2011). Various adaptation options (Donatelli *et al*., 2010; Vadez *et al*., 2012) are available such as- a.) Changes in plant behavior; b.) Creating micro environment and c.) Manipulating agronomic practices, but the options need to be economically feasible, ecologically sound and socially acceptable. Various agronomic options *i.e.* Selection of improved varieties, change in sowing windows, efficient irrigation management, and efficient fertilizer management can minimize the impacts of climate change by sustaining the productivity.

In general, if pests and diseases are excluded from the 'yield declining factor', productivity of any crop is mainly depends upon the plant population, irrigation, fertilizer, and other nonmonetary inputs, like sowing time. Currently major emphasis are given on efficient management of resources such as water, nutrients to itinerant the stagnant productivity. To test the response of these options, field experiment may be an expensive approach both in terms of money and time, hence already calibrated and validated crop model may be the effective tool to simulate the options in better manner and a quick response may offers to farmers, researchers and policymakers.

By keeping the facts in mind, projected productivity of wheat for the period of 2015-2030 in Haridwar district is assessed under various sowing dates and nitrogen levels. Simulation was carried out in DSSAT 4.5. For this purpose PRECIS-RCM (Providing REgional Climates for Impact Studies-Regional Climate Model) climate data have been used to generate the weather file along with four CO_2 scenarios. Soil and genetic coefficient files generated for model evaluation (discussed in Chapter V) were used in present study. Crop management files were developed as per the recommended management practices follwed in the experiment conducted during 2011-12 and 2012-13 (Pranuthi, 2016).

6.2 PRECIS RCM Predicted Climate Scenario

In present study daily weather data (daily precipitation, maximum temperature and minimum temperature) for the period 2015-30 was taken from PRECIS RCM predicted climatic scenarios (Dubey *et al.* 2015b; Tripathi *et al*, 2015). Daily solar radiation was derived using minimum (ºC) and maximum temperature (Samani, 2000) and used to prepare the weather file in DSSAT model along with daily precipitation, maximum temperature and minimum temperature.

Table 6.1: Average of PRECIS RCM projected weather data used in simulation of future crop yield.

Year	**Months**												**Average of WGP**
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
	Solar Radiation (MJ m^{-2} day^{-1})												
2015-20	14.7	17.9	22.3	26.9	28.7	24.4	19.8	17.9	19.0	20.1	17.9	15.3	19.1
2021-25	**13.0**	**16.3**	**22.0**	27.0	28.7	25.2	20.8	18.8	19.4	**19.3**	**17.1**	**14.1**	**18.3**
2026-30	13.5	17.1	22.5	27.6	25.6	26.9	20.7	18.2	19.5	19.9	17.3	14.2	18.7
	Total Rainfall (mm)												
2015-20	21.0	14.3	44.1	20.3	15.7	227.1	342.7	274.8	167.7	1.1	3.8	9.0	121.0
2021-25	**37.1**	**42.0**	9.9	**56.3**	15.5	133.3	250.3	188.2	123.5	**68.2**	**7.0**	**57.5**	**194.8**
2026-30	24.7	3.3	12.4	20.6	70.6	50.4	344.9	305.5	132.8	21.3	13.1	6.2	89.2
	Maximum Temperature (°C)												
2015-20	19.7	22.9	25.8	31.5	35.6	31.8	31.9	31.1	31.7	29.5	27.1	22.4	24.8
2021-25	**16.8**	**19.8**	**25.2**	**31.4**	35.7	32.7	33.0	31.9	32.4	30.8	27.3	**20.9**	**23.5**
2026-30	17.2	20.6	26.4	31.5	32.6	35.2	33.3	32.0	32.6	30.7	27.1	21.0	24.1
	Minimum Temperature (°C)												
2015-20	6.7	9.8	12.2	16.9	21.3	21.8	25.3	25.0	22.6	15.5	10.5	6.7	10.5
2021-25	6.6	8.8	11.9	16.7	21.4	22.1	25.8	25.2	23.0	17.9	12.1	7.4	10.5
2026-30	6.1	8.6	12.6	16.1	20.8	23.2	26.0	25.6	23.1	17.1	11.8	7.4	10.5

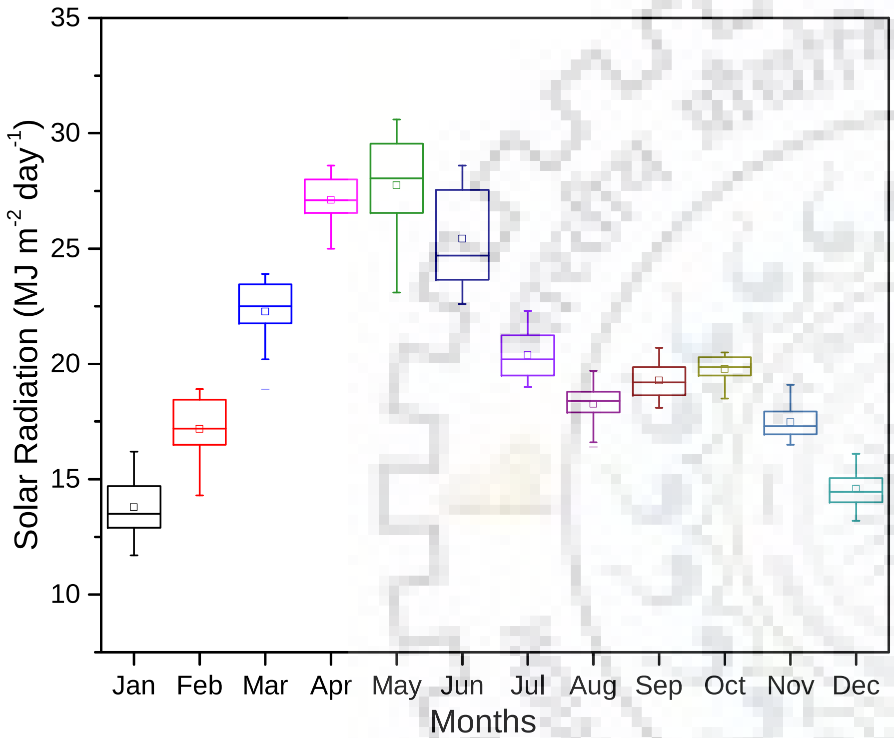


Figure 6.1a: Box plot of monthly solar radiation (MJ m^{-2} day^{-1}) for the period of 2015-2030.

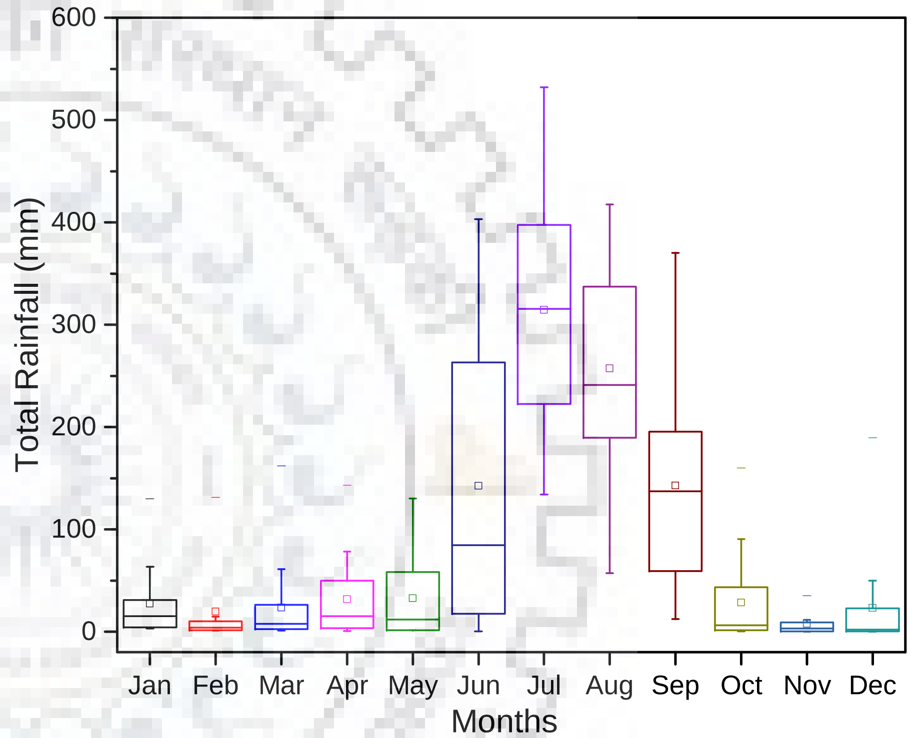


Figure 6.1b: Box plot of monthly rainfall (mm) for the period of 2015-2030.

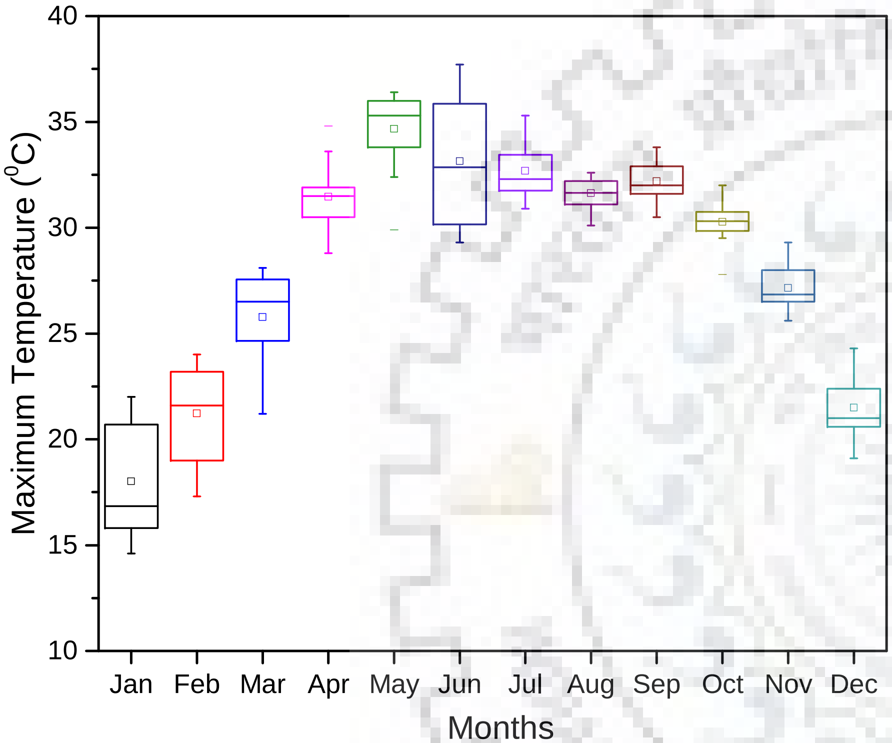


Figure 6.1c: Box plot of monthly maximum temperature (^{0}C) for the period of 2015-2030.

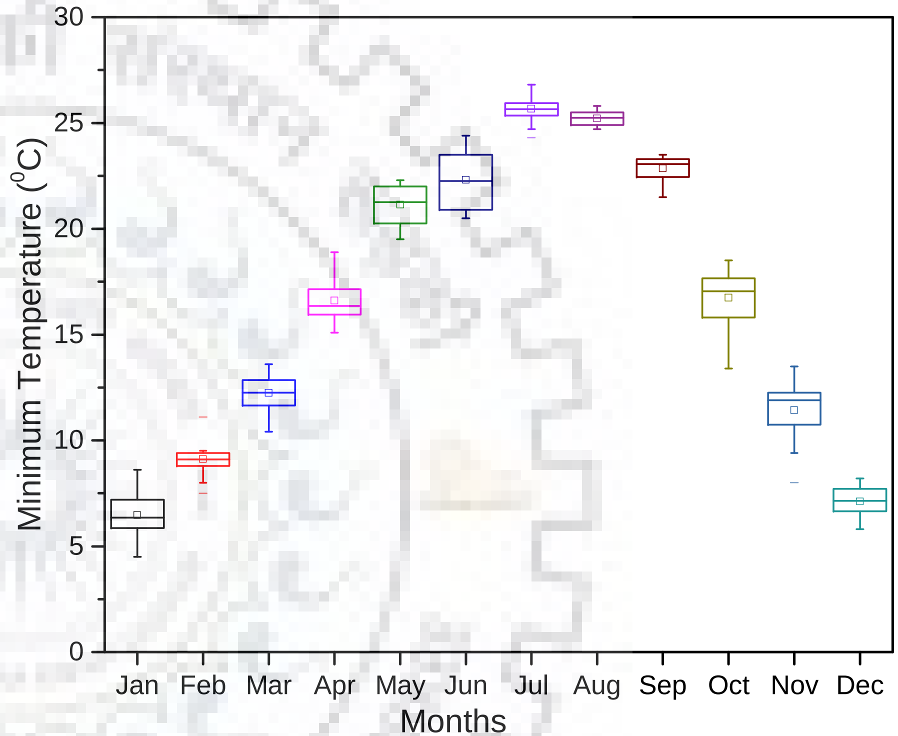


Figure 6.1d: Box plot of monthly minimum temperature (^{0}C) for the period of 2015-2030.

Monthly average values of data set used in the study is depicted in Figure 6.1a-6.1d. and five year average (2015-20, 2021-25 and 2026-30) of the same is presented in table 6.1. Solar radiation presnted in table 6.1 revealed that during the period of 2021-25 the values in five month (*in bold fonts*) *i.e.* November-March, which is the major period of wheat cultivation ranges in lower than the avergae of 2015-20 and 2026-30. Rainfall data revealed that during the period of 2021-25 the values in five month (*in bold fonts*) i.e. October-April (except march) is observed higher than the avergae of 2015-20, 2026-30. Similarly, maximum temperature during December to April is comparatively low as compare to the average of 2015-20, 2026-30. No any definte trend was noticed for minimum temperature in among the study period.

Over the years of 2015-2013, PRECIS RCM predicted minimum temperature, maximum temperature, rainfall and solar radiation during wheat growing period (WGP) ranges from 9.9-11.7 °C, 21.9-26.4 °C, 12-419 mm and 17.2-20.2 MJ m^{-2} day^{-1} respectively. Solar radiation, and maximum temperature (°C) were recorded lower during 2021-2025, which may be attributed to increased amount of rainfall during this period. The same obeservation were noticed in figure 6.2.

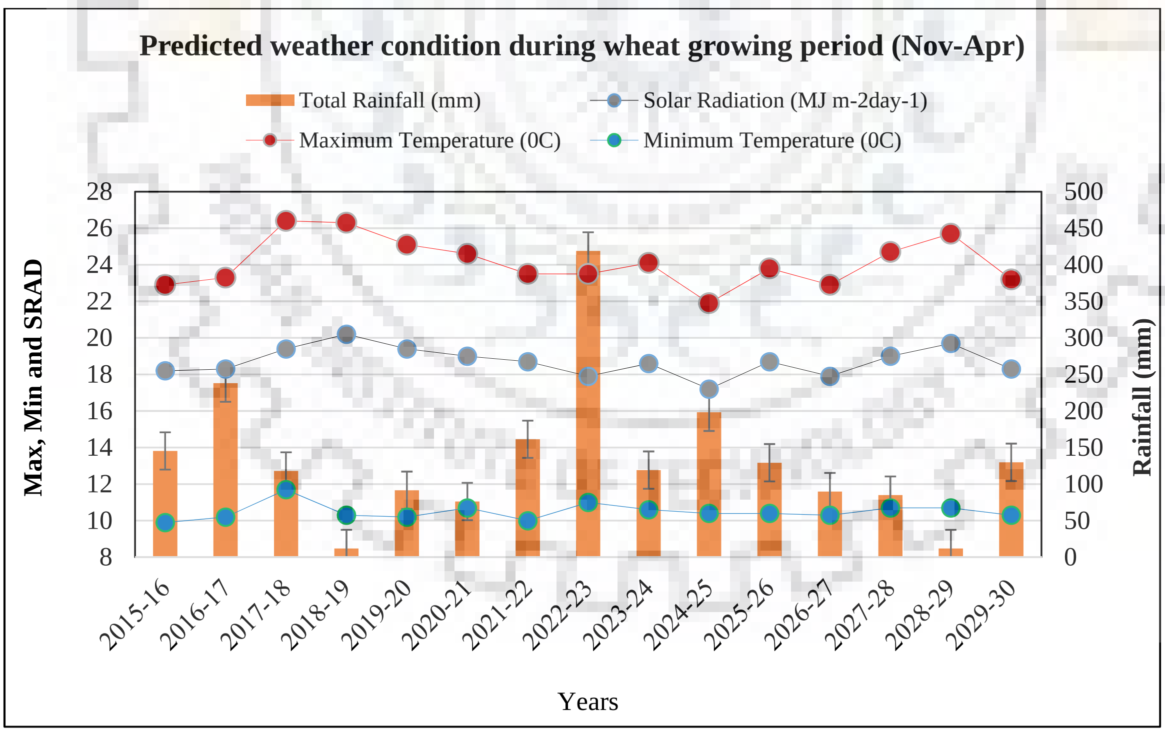


Figure 6.2: Predicted weather condition during wheat growing period (Nov-Apr)

6.3 Future of wheat productivity and adoption strategies

DSSAT CERES wheat model was used to test the sustainability of experiment in the future scenario. For this purpose PRECIS-regional climate model derived weather data were used for simulating the wheat productivity of Haridwar district during the period of 2015-2030. Further, to suggest the agronomic adoptions for improving the wheat productivity in the future (2015-2030) changing climate, the model was run by taking five dates CO_2 of sowing and five nitrogen doses under four CO_2 scenarios. The CO_2 scenario used in the model was kept same as recorded during field experiments in 2011-12 and 2012-13. The treatments detail used in the simulation model are as follows:

6.3.1 Details of treatments:

Main treatments: CO_2 scenarios (Four) :

T_0 = Control;

T_1 = CO_2 (700 ± 50 ppm) one application per week;

T_2 = CO_2 (700 ± 50 ppm) two applications per week;

T_3 = CO_2 (700 ± 50 ppm) three application per week.

Sub treatments 1: Dates of sowing (Six) :

D_1= 01-November
D_2= 07-November
D_3= 14-November
D_4= 21-November
D_5= 28-November
D_6= 05-December

Sub treatments 2: Levels of Nitrogen (Five) :

N_1=40 kg N_2 ha^{-1}
N_2=60 kg N_2 ha^{-1}
N_3=80 kg N_2 ha^{-1}
N_4=100 kg N_2 ha^{-1}
N_5=120 kg N_2 ha^{-1}

The sowing date of the crop and nitrogen levels are the most important production influencing parameters. This study evaluates the impact of these parameters on production under different CO_2 scenario. In the selected study region, sowing period of wheat varies from first week of November to first week of December.

6.3.2 Projected yield under different CO_2 scenarios

Wheat grain yield predicted for the period of 2015-16 to 2029-30 under various CO_2 enrichment scenarios is presented in Table 6.2. Result indicates that the projected productivity of wheat during the period of 2021-25 would be low in each CO_2 emission scenarios in comparison to period 2016-20, and 2026-30.

Table 6.2: Predicted grain yield (kg ha^{-1}) under different CO_2 scenarios during 2015-2030.

Statistical parameters	2016-2020				2021-2025				2026-2030			
	T_0	T_1	T_2	T_3	T_0	T_1	T_2	T_3	T_0	T_1	T_2	T_3
Mean yield (kg ha^{-1})	5654	6116	6854	7153	5499	5966	6667	6956	5764	6247	6971	7291
Standard error	145.8	139.0	132.1	121.3	170.6	179.3	242.3	267.3	95.9	137.0	119.5	132.2
Minimum (kg ha^{-1})	5316	5817	6626	6954	5067	5626	6194	6404	5528	5958	6664	6959
Maximum (kg ha^{-1})	5986	6448	7184	7449	5830	6302	7095	7419	5985	6601	7208	7573

This low productivity could be attributed to the abberation in weather condition marked with excessive and untimely rain during the wheat growing period (Fig. 6.2). However this can be augmented by CO_2 enrichment treatment. The average grain yield predicted through model under T_0, T_1, T_2 and T_3 is 5654, 6116, 6854 and 7153 kg ha^{-1} for 2016-2020 period 5499, 5966, 6667 and 6956 kg ha^{-1} for 2021-2025 and 5764, 6247, 6971 and 7291 kg ha^{-1} during 2026-2030 respectively. Standard error resulted during the period of 2021-2025 is quite higher as comapre to 2016-2020 and 2026-2030 which indicates the variation in yield during 2026-2030. The result is in line of confirmation that the increasing CO_2 level will always be beneficial. The result agrees with our previous findings (Dubey, *et al.*, 2014).

6.4 Assessment of yield under different Agronomic options and CO_2 scenarios

Effort has been made to find out the best agronomic measures to cope up with the adverse imapct of climate change for sustainable production of wheat in the study area. For this purpose, different sowing windows and nitrogen rates were tested under four CO_2 scenarios. Results in detail are discussed as under-

6.4.1 Assessment of optimum sowing dates

The model was run by taking six sowing dates D_1= 01-November, D_2= 07-November, D_3= 14-November, D_4= 21-November, D_5= 28-November and D_6= 05 December corresponding to different CO_2 enrichment treatment (T_0-T_3) with the objective to find out the appropriate sowing date of wheat crop *cv.* PBW 343 for this location under different CO_2 scenarios. Simulation result obtained is presented in Table 6.3.

Table 6.3: Simulated grain yield (kg ha^{-1}) as affected by periodical CO_2 enrichments and dates of sowing.

Average grain yield during 2016-20							
Treatments	**D_1**	**D_2**	**D_3**	**D_4**	**D_5**	**D_6**	**Average**
T_0	4696	4954	5502	5753	5667	5103	**5279**
T_1	5072	5362	5957	6226	6136	5513	**5711**
T_2	5671	6055	6695	7006	6919	6197	**6424**
T_3	5849	6253	6989	7318	7235	6478	**6687**
Average	5322	5656	**6286**	**6576**	**6489**	5823	**6025**
CO_2 effect	P=0.05: Sig; CD (Tukey): 96 Kg ha^{-1}; SE ±: 46.3						
Date of sowing	P=0.05: Sig; CD (Tukey): 123.5 Kg ha^{-1}; SE ±: 59.72						
Average grain yield during 2021-25							
T_0	3907	4097	4460	4640	4431	4000	**4256**
T_1	4160	4335	4749	5027	4783	4307	**4560**
T_2	4666	4798	5281	5621	5370	4890	**5104**
T_3	4870	5007	5471	5866	5611	5107	**5322**
Average	4401	4559	**4990**	**5289**	**5049**	4576	**4810**
CO_2 effect	P=0.05: Sig; CD (Tukey):74.0 Kg ha^{-1}; SE ±: 35.8						
Date of sowing	P=0.05: Sig; CD (Tukey): 95.7 Kg ha^{-1}; SE ±: 46.25						
Average grain yield during 2026-30							
T_0	4919	5270	5679	5852	5638	5084	**5407**
T_1	5217	5569	6076	6357	6119	5505	**5807**
T_2	5803	6246	6832	7121	6935	6230	**6528**
T_3	6101	6529	7168	7450	7267	6522	**6840**
Average	5510	5903	**6439**	**6695**	**6490**	5836	**6145**
CO_2 effect	P=0.05: Sig; CD (Tukey): 109 Kg ha^{-1}; SE ±: 52.6						
Date of sowing	P=0.05: Sig; CD (Tukey): 140.3 Kg ha^{-1}; SE ±: 67.5						
Average grain yield during 2016-30							
T_0	4736	5002	5471	5713	5556	5005	**5247**
T_1	5059	5334	5867	6191	6016	5411	**5646**
T_2	5650	5970	6572	6939	6779	6108	**6336**
T_3	5889	6212	6855	7249	7093	6393	**6615**
Average	5333	5630	**6191**	**6523**	**6361**	5730	**5961**
CO_2 effect	P=0.05: Sig; CD (Tukey): 93 Kg ha^{-1}; SE ±: 45.1						
Date of sowing	P=0.05: Sig; CD (Tukey): 120.5 Kg ha^{-1}; SE ±: 58.28						

Grain yield was significantly increased in among the sowing dates by each increase in the CO_2 levels. Results revealed that D_4 was the most optimum date of sowing followed by D_5 and D_3. During the period of 2016-2020 the average predicted grain yield under various sowing dates

(D_1, D_2, D_3, D_4, D_5 and D_6) was 5322, 5656, 6286, 6576, 6489 and 5823 kgs ha^{-1}. At D_3, D_4 and D_5 the yield obtained was significantly higher (CD=123.5) in each CO_2 scenarios as compare to D_1, D_2 and D_6. Similar pattern were noticed for 2021-25 and 2026-30, though the yield obtained during 2021-25 was low as compared to 2016-2020 and 2026-30. Model result confirms that the optimum sowing window for the wheat *cv.* PBW-343 for this location varied from D_3 to D_5 (Nov. 14-28). Simulated result agrees with the findings of Singh *et al*. (2013) and Singh *et al*. (2015). Similar adoption options was also suggested by Mall *et al.* 2001 using SPAW model.

6.4.2 Assessment of optimum nitrogen levels

The model was run by taking five nitrogen levels *i.e.* N_1= 40 kg ha^{-1}, N_2= 60 kg ha^{-1}, N_3= 80 kg ha^{-1}, N_4= 100 kg ha^{-1} N_5= 120 kg ha^{-1} corresponding to different CO_2 enrichment treatment (T_0-T_3) with the objective to find out the appropriate nitrogen dose for wheat crop *cv.* PBW 343 under various CO_2 scenarios. Simulation results obtained are presented in Table 6.4.

The average yield obtained under N_1, N_2, N_3, N_4 and N_5 during the period of 2016-20 was 5765, 7066, 7810, 8019 and 8020 Kg ha^{-1} and the similar pattern of yield was noticed for 2021-25 and 2026-30. The analysis revealed that over the entire simulation period (2016-20, 2021-25 and 2026-30) the difference was insignificant between N_3-N_4 and N_4-N_5. Grain yield was significantly increased with each increase in the nitrogen application but decreases over the time. The negative pattern of yield over the time was compensated with the positive impact of CO_2. In each scenarios, highest grain yield was noticed under N_5 which was at par with N_4 and N_3 means statistically there were no any significant change has been noticed. Moreover the differences in yield are much closer in N_4 and N_5 thus the optimum nitrogen application for the wheat *cv.* PBW-343 for this location may varies from 100-120 kg ha^{-1}. This result is in agreement with the study proposed by Pal *et al.*, (2003) and Gangaiah *et al.*, (2014).

Table 6.4: Simulated grain yield (kg ha^{-1}) as affected by periodical CO_2 enrichments and nitrogen levels.

Average grain yield during 2016-20						
Treatments	**N_1**	**N_2**	**N_3**	**N_4**	**N_5**	**Average**
T_0	5004	6099	6707	6856	6856	**6305**
T_1	5449	6647	7324	7502	7502	**6885**
T_2	6157	7566	8383	8624	8626	**7871**
T_3	6451	7952	8827	9093	9095	**8284**
Average	5765	7066	**7810**	**8019**	**8020**	**7336**
CO_2 effect	P=0.05: Sig; CD (Tukey): 230 Kg ha^{-1}; SE ±: 109.7					
N_2 effect	P=0.05: Sig; CD (Tukey): 265 Kg ha^{-1}; SE ±: 126.7					
Average grain yield during 2021-25						
T_0	4810	5872	6283	6410	6463	**5968**
T_1	5175	6355	6825	6974	7060	**6478**
T_2	5773	7155	7747	7937	8058	**7334**
T_3	6022	7490	8130	8339	8471	**7690**
Average	5445	6718	**7246**	**7415**	**7513**	**6867**
CO_2 effect	P=0.05: Sig; CD (Tukey): 217 Kg ha^{-1}; SE ±: 103.8					
N_2 effect	P=0.05: Sig; CD (Tukey): 251 Kg ha^{-1}; SE ±: 119.9					
Average grain yield during 2025-30						
T_0	5118	5930	6101	6106	6106	**5872**
T_1	5541	6458	6666	6673	6673	**6402**
T_2	6222	7351	7649	7664	7664	**7310**
T_3	6500	7722	8059	8078	8078	**7687**
Average	5845	6865	**7119**	**7130**	**7130**	**6818**
CO_2 effect	P=0.05: Sig; CD (Tukey): 173 Kg ha^{-1}; SE ±: 82.8					
N_2 effect	P=0.05: Sig; CD (Tukey): 200 Kg ha^{-1}; SE ±: 95.66					
Average grain yield during 2016-30						
T_0	4986	5965	6347	6435	6452	**6037**
T_1	5398	6485	6921	7026	7053	**6577**
T_2	6061	7357	7909	8049	8088	**7493**
T_3	6335	7721	8321	8477	8519	**7875**
Average	5695	6882	**7375**	**7497**	**7528**	**6995**
CO_2 effect	P=0.05: Sig; CD (Tukey): 204 Kg ha^{-1}; SE ±: 97.2					
N_2 effect	P=0.05: Sig; CD (Tukey): 235 Kg ha^{-1}; SE ±: 112.3					

6.5 Conclusion

Present study provides a glimpse of future scenarios of wheat cultivation in Haridwar district of Uttarakhand. From the study it is obvious that the uneven changes in weather conditions may prevails during 2021-25, due to which grain productivity may decline. This low productivity could be attributed to the abberation in weather condition marked with excessive and untimely rain during the wheat growing period. Constantly increasing CO_2 level will play a positive role to achieve the higher productivity. Also it is clear that under the changing climate, there may not be much shift in the sowing dates and nitrogen level which is currently in practice. To achieve the optimum productivity of wheat, the crop need to be sown between November 14-28, and the optimum dose of nitrogen may be 100-120 kg ha^{-1}.

Chapter –7

SUMMARY AND CONCLUSIONS

7.1 Summary

Atmospheric CO_2 concentration, which particularly affects photosynthesis of C_3 plants, has already risen from 280 ppm to 375 ppm in the past and based on the A_1B IPCC scenario is predicted to double at the middle of this century (Meehl *et al.*, 2007). Concern about the predicted changes in climate and the rapid rise in concentration of the atmospheric CO2 has prompted strong interest in the response of agricultural food production to these changes. Plant photosynthetic processes and consequently plant growth are known to be directly affected by elevated CO_2 (Kimball *et al.*, 2002; Long *et al.*, 2005). The elevated atmospheric CO_2 positively affected the crop growth and productivity, both in terms of quantity and quality by the increased photosynthesis, nutrient and water use efficiency.

The beneficial effects of increased concentration of atmospheric CO_2 on wheat plants included the reduction in stomatal conductance and transpiration, improved water-use efficiency, increased rates of photosynthesis and light-use efficiency. Amthor (2001) and Kimball (1983) critically reviewed several studies on wheat plants grown with enriched CO_2 in the green houses, laboratory chambers, open top chambers, closed top chambers and free air CO_2 enrichment (FACE) and reported the increased grain yield ranging from 4-43%. Laboratory and controlled condition studies on wheat proved that the elevated CO_2 level not only enhance the rate of photosynthesis (Pal *et al.*, 2005) also increase the number of tillers, plant biomass and grain yield depending upon the genotype, climate, and management practices (Uprety *et al.*, 2009).These findings came from the studies undertaken in controlled environments or enclosures, it needs to be tested in field condition. Looking to the aforementioned, an experimental field study was carried out with the objectives to (1) assess the effect of periodical CO_2 enrichment on microclimatic change in wheat crop. (2) evaluate the effect of periodical CO_2 enrichment on growth, development, yield and quality of wheat crop. (3) calibration and evaluation of the DSSAT CERES-Wheat model using field experimental data. (4) suggestion for the agronomic ways and means to improve the productivity of wheat under changing climate.

The study was carried out during *Rabi* season of the years 2011-12 and 2012-13 at the demonstration farm of the Department of Water Resource Development and Management, Indian Institute of Technology Roorkee, Roorkee (Uttarakhand).The field experiment was laid down in randomized block design with 4 treatments (T_0 = Control; T_1 = CO_2 (700 ± 50 ppm) once /week (Monday); T_2 = CO_2 (700 ± 50 ppm) twice /week (Monday & Wednesday) and T_3 = CO_2 (700 ± 50 ppm) thrice / week (Monday, Wednesday & Friday) and three replications. The soil condition was silt loam in texture and medium in fertility. Agro climatic condition is classified as sub humid.

Field observations were recorded on microclimate change (CO_2 and temperature) prevails in the experimental plots, before and after the application of CO_2. In general, after the application of CO_2 in the crop, the leaf temperature, within canopy temperature and above canopy temperature rose up to 0.2-0.5 °C. There was no physical abnormality noticed due to this rise in temperature after CO_2 application.

Further, the field observations pertaining to growth and development were collected at each 20 days interval in all the treatments. Analysis of observations revealed that the plant height, leaf area, flag leaf area, plant dry matter and leaf area index was significantly increased with increasing the frequency of CO_2 application. Significant difference between the treatments was recorded in almost all the growth and development observations at 100 days after sowing. Days taken to boot leaf initiation, ear emergence, anthesis, flowering and physiological maturity was reduced by 2-3 days with CO_2 enrichment.

As for as yield and yield attributes are concern the recorded observations showed a significant improvement in grain yield (kg ha^{-1}), straw yield (kg ha^{-1}), biological yield (kg ha^{-1}), harvest index (%), effective tiller (%), number of grain/spike, grain weight $plant^{-1}$ (g) and test weight or 1000 grain weight (g). Average grain yield (kg ha^{-1}) during the year 2011-12 was recorded as 4870, 5200, 6250 and 6570 kg ha^{-1}, whereas during 2012-13 it was recorded as 4570, 4840, 5570 and 5830 kg ha^{-1} in T_0, T_1, T_2 and T_3 treatments respectively. Reduced grain yield during 2012-13 was noticed due to untimely rain at anthesis and maturity stages. Effective tiller (%), number of grains $pike^{-1}$, grain weight $plant^{-1}$ (g) and grain test weight were significantly increased with CO_2 treatments. Length (mm) and width (mm) of grain was marginally improved with CO_2 application. Biochemical grain quality observations revealed that the total protein content (%) and nitrogen content (%) decreased due to CO_2 enrichment whereas as, total carbohydrate contents (%) increased significantly. The content of K (%), Mg (%) and S (%) was slightly increased but the content of P (%) and Ca (%) was decreased in the grains of CO_2 treatment plots.

In addition to this, DSSAT CERES-Wheat model was calibrated for the wheat *cv.* PBW 343 under the soil climatic conditions of Roorkee. For this purpose a separate field experiment was carried out with 4 dates of sowing *i.e.* 15th Nov 2013, 22nd Nov. 2013, 29th Nov. 2013 and 06th Dec. 2013 by adopting the proper agronomic practices. Data pertaining to growth and development *viz.* days taken to emergence (DAS), ear emergence (DAS), anthesis (DAS), maturity (DAS), product weight (kg dm/ha), grain yield (kg ha^{-1}), product unit weight (g dm), product number (number m^{-2}) or number of grain/m^2,product number (number $group^{-1}$) or grain number ear^{-1}, product harvest index (ratio), maximum leaf area index, final shoot number (m^2), canopy (tops) weight (vegetative +grain) kg ha^{-1}) and vegetative weight (kg ha^{-1}) were recorded. Soil, weather and crop management files were created to run the DSSAT-CERES model and to generate the genetic coefficient of *cv.* PBW343. The genetic coefficient developed through the iterative process is given below:

P_1=20.0; P_1D=68.0; P_5=550.0, G_1=19.0; G_2= 44.0; G_3= 1.2 and PHINT: 95.0

Further, the DSSAT model was evaluated for wheat *cv.* PBW 343 grown under different CO_2 treatments in the field experiments conducted during the year 2011-12 and 2012-13. The DSSAT model was run by taking the genetic coefficient file already developed and generating the soil, weather and crop management files from the field experimental data. The model simulated outputs on days taken to emergence, days taken to anthesis, days taken to physiological maturity, grain yield (kg ha^{-1}), straw yield (kg ha^{-1}), biological yield (kg ha^{-1}), grain test weight, number of grains m^{-2}, grains $earhead^{-1}$, harvest index, maximum LAI and grain N content were used for statistical analysis to compare with the actual field observations. Model output data and field observed data were insignificantly different. This proves that the DSSAT CERES Wheat model can be used for the simulation of wheat crop yield for soil climatic condition of Roorkee, Haridwar.

In order to assess the future climate scenario of Haridwar, PRECIS-RCM derived daily rainfall (mm); maximum temperature (°C) and minimum temperature (°C) was taken for the period 2015-2030. Daily solar radiation was calculated using the temperature data. DSSAT compatible weather file was generated from bias corrected PRECIS RCM data for the period 2015-2030. Soil, genetic coefficient and crop management files were taken from the evaluation study. DSSAT CERES wheat model was run to forecast the productivity of wheat in Haridwar district under changing climate scenario. Simulation results during 2015-2030 showed that the yield may decline with the advancing of climate change but CO_2 intervention will compensate the loss in yield occurred due to higher temperature and erratic rainfall pattern (climate change).

Moreover, the DSSAT model was used to develop the agronomic strategies of the future for increasing productivity of wheat by making changes in crop management practices, which included 6 dates of sowing (Nov.01, Nov. 07, Nov. 14, Nov 21, Nov. 28 and Dec 6) and 5 level of N (kg ha^{-1}) application (40, 60, 80,100 & 120). These options were tested under four levels of CO_2 enrichment scenarios as taken in the field experiment. Result revealed that the productivity of wheat crop in the next 15 years would be high when the wheat crop is managed by sowing between November, 14-28, and by applying N at the rate of 100-120 kg ha^{-1}.

7.2 Conclusions of the study

Following conclusions are drawn from the present study

1. A temporary and marginal increase of 0.2-0.5^{0}C in leaf temperature, within canopy temperature and above canopy temperature was noticed in the CO_2 treated plots. Practically there was no abnormality shown by the crop with such a change in temperature regime probably this increase was purely temporary in nature as the crop grown was under the open field condition.
2. The average ambient CO_2 concentration in the experimental plot was recorded as 309 ppm during 2011-12 and 319 ppm during 2012-13 Observations showed that the CO_2 level rose to about 700 ± 50 ppm at the time of application which subsided to 500±10ppm within 10 minutes of application and further subsided to become normal within 20 minutes.
3. Significant improvement in growth and yield was noticed due to CO_2 enrichment however, the effect was insignificant for phenological development such as ear emergence, anthesis, and flowering and no. of grain/spike, harvest index, grain length and width. Grain protein and nitrogen content was significantly decreased and carbohydrate content was increased due to CO_2 enrichment. Other macro nutrients such as K, Mg and S increased but P and Ca decreased insignificantly.
4. The calibration of DSSAT CERES wheat model using field experimental data of four dates of sowing conducted during 2013-14 showed that the difference in the observed and simulated growth, development and yield parameters was within the acceptable limit. This proved that the application of DSSAT CERES wheat model is acceptable to soil climatic condition of Roorkee. Genetic coefficient of *cv*. PBW 343 was developed through iterative process.

5. The DSSAT CERES wheat model was evaluated using field experimental data of four CO_2 enrichment treatments conducted during 2011-12 and 2012-13. Model simulated growth and yield result was insignificantly different from the actual experimental result. This proves that the model could be effectively used to replicate field experimental results of wheat *cv*. PBW 343.
6. DSSAT CERES Wheat simulation during 2015-2030 showed that the yield will decline with the advancing of climate change but CO_2 intervention will compensate the loss in yield occurred due to higher temperature and erratic rainfall pattern (climate change).
7. The DSSAT was used to develop adaptation strategies for the future (2015-2030) under the climate change and higher CO_2 scenarios. The result showed that the better yield can be obtained by sowing the wheat between 14-28 November, and adopting the nitrogen application between 100-120 kg/ha. The study also reveals that the response of periodical enrichment of CO_2 on wheat *cv*. PBW-343 under the soil climatic conditions of Roorkee (Haridwar, Uttarakhand, India) is beneficial to increase its productivity.

7.3 Major Research Contributions

Major research contributions of this study are as follows:

1. The periodical CO_2 enrichment under field was carried out using locally available low-cost materials (Fire extinguishing quality CO_2, iron rods and normal plastic sheet) as an alternative technique to FACE and OTC.
2. The use of CO_2 has been undertaken mostly with the objectives of climate change impact analysis but this study had the additional objective of testing its fertilization effect on wheat.
3. The CERES model has been calibrated and evaluated for the soil and climatic condition of the Roorkee Uttarakhand.
4. The genetic coefficient of wheat *cv*. PBW 343 has been developed which may help in the simulation studies in line of current research.
5. Future scenarios of wheat productivity along with the agronomic adoption strategies for the Haridwar district of Uttarakhand is suggested.

7.4 Scope for Future Research

1. Further researches could be directed towards varietal screening with CO_2 enrichment to identify and popularize CO_2 responsive varieties.

2. This study paves the way for researchers towards studying the response of various Indian varieties under CO_2 enriched conditions, so that the varieties that respond more positively both in term of quantity and quality can be recommended for cultivation.
3. In order to validate the study it need to be replicated few more years using various genotypes and cultural practices.
4. The effect of CO_2 enrichment under field conditions in response to varying levels of water, nutrient etc. can be undertaken to improve its efficiency.
5. The CO_2 enrichment technique developed needs to be tested along with pre-established FACE and OTC techniques.

PHOTOGRAPHS OF FIELD EXPERIMENT (2011-12 & 2012-13)

Field Preparation

Layout of Wheat field

Line Sowing of Wheat by Dibbler

Installation and Testing of CO_2 distributaries

CO2 distributaries in different CO2 treatment plot

Poly- Growth Chamber during 2011-12

Crop under Growth Chamber

Poly- Growth Chamber during 2012-13 (Different CO2 Treatments)

Replacing Growth Chamber after heavy rain

Inspection of crop

Crop at flowering stage: Showing different CO_2 treatment response

Chamber Removed at Ear Initiation stage

Crop at flowering stage

Crop at milking stage

Crop at Grain filling stage

Crop at Dough stage

Crop at harvesting stage

PUBLICATION FROM THE WORK

RESEARCH PAPERS

Dubey, S. K., Tripathi, S. K., & Pranuthi, G. (2015). Effect of Elevated CO_2 on Wheat Crop: Mechanism and Impact. *Critical Reviews in Environmental Science and Technology*, *45*(21), 2283-2304.

Dubey S.K., Tripathi S.K., Pranuthi G., YadavReshu (2014) Impact of projected climate change on Wheat varieties in Uttarakhand, India. *Journal of Agrometeorology* 16 (1): 26-37.

BOOK CHAPTER PUBLISHED

Tripathi S.K., Pranuthi, G. **Dubey**, **S.K.** Kumar G.V. and Mfwango L. (2013) Characterization of crop productivity using DSSAT for South West Uttarakhand India. In : Food and Environnent II by Brebbia C.A. and Popov, B., WIT Press Bostan UK. pp 113-122(doi:10.2495/FENVI30141).

Dubey, S.K., Tripathi, S.K., Pranuthi G. (**2015**) 21st Century Climate Change Scenario of Haridwar District in Uttarakhand. In: Water Management and Climate Smart Agriculture by R. Subbaiah and G.V. Prajapti. Volume 2 pp 1-19 published by Junagarh Agriculture University Gujarat.

CONFERENCES/SYMPOSIUM

S.K.Tripathi, **S.K.Dubey** and G. Pranuthi (2015) PRECIS RCM based Climate change trend and DSSAT Forecasted Crop productivity in Hardwar district. Presented at the *TROPMET 2015 National Symposium on Weather & Climate Extremes* from Feb. 15-18, 2015 held at Chandigarh, India.

S.K. Tripathi, G.Pranuthi and **S.K. Dubey** (2014) Climate Change Assessment Using PRECIS-RCM Data for Hardwar District of Uttarakhand. Presented in ***International Annual Meetings***, "Grand Challenges—Great Solutions," organized by *American Society of Agronomy on* Nov. 2-5, 2014, at Long Beach, CA.

Abebe, A. L., Pathak, H., & Singh, S. D. (2016). Growth and yield of wheat (*Triticum aestivum* L.) with elevated atmospheric carbon dioxide and temperature in north-west India. *Current Advances in Agricultural Sciences,* 8 (**1**), 24-27.

Addiscott, T.M. and A.P. Whitmore. (1987). Computer simulation of changes in soil mineral nitrogen and crop nitrogen during autumn, winter and spring. *Journal of Agriculture Science* **109**:141-157.

Aggarwal, P. K., & Sinha, S. K. (1993). Effect of probable increase in carbon dioxide and temperature on wheat yields in India. *Journal of Agricultural Meteorology* 48 **(5)**: 811-814.

Aggarwal, P.K. (2008). Global climate change and Indian agriculture: impacts, adaptation and mitigation. *Indian Journal of Agriculture Science* 78 **(11)**: 911-919.

Agrawal, M. (2012). Influence of elevated level of CO_2 on plants. In: *Modern Trends in Applied Terrestrial Ecology by Modern Trends in Applied Terrestrial Ecology,* edited by Ambasht, R.S. Ambasht, N.K. Springer pp 1- 225.

Ahuja L.R., Ma, L., Fang, Q.X., Saseendran S.A., Islam, A., and Malone, R.W. (2014). Computer Modeling: Applications to Environment and Food Security. In: Neal Van Alfen, editor-in-chief. *Encyclopedia of Agriculture and Food Systems* **2**:337-358.

Ainsworth, E. A. & Long, S. P. (2005). What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. *New Phytologist* 165 **(2)**: 351-372.

Ainsworth, E. A., & Rogers, A. (2007). The response of photosynthesis and stomatal conductance to rising [CO_2]: mechanisms and environmental interactions. *Plant, cell & environment* 30 **(3):** 258-270.

Alexandrov, V. A., & Hoogenboom, G. (2000). The impact of climate variability and change on crop yield in Bulgaria. *Agricultural and Forest Meteorology* 104 **(4)**: 315-327.

Allen Jr, L.H., & Prasad, P.V. (2004). Crop responses to elevated carbon dioxide. *Encyclopedia of plant and crop science. Marcel Dekker, New York,* 346-348.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). FAO Irrigation and drainage paper No. 56. *Rome: Food and Agriculture Organization of the United Nations* **56:** 97-156.

Alocilja, E. C. and Ritchie J. T. (1991). A Model for the Phenology of Rice in Hodges, T. (ed.), *Predicting Crop Phenology*, CRC Press, Boca Raton, Florida, pp. 181–189.

Amiri, E., Rezaei, M., Bannayan, M., & Soufizadeh, S. (2013). Calibration and Evaluation of CERES Rice Model under Different Nitrogen-and Water-Management Options in Semi-Mediterranean Climate Condition. *Communications in soil science and plant analysis*, 44(**12**), 1814-1830.

Amthor, J. S. (2001). Effects of atmospheric CO_2 concentration on wheat yield: review of results from experiments using various approaches to control CO_2 concentration. *Field Crops Research* 73 **(1)**: 1-34.

Anonymous (2016). CO_2 Now. (https://www.co2.earth/): [access on 22.04.2016].

Aranjuelo, I., Sanz-Sáez, Á., Jauregui, I., Irigoyen, J. J., Araus, J. L., Sánchez-Díaz, M., & Erice, G. (2013). Harvest index, a parameter conditioning responsiveness of wheat plants to elevated CO2. *Journal of experimental botany*, doi: 10.1093/jxb/ert081.

Archer, D. (2011). Global warming: understanding the forecast. 2nd Edition, ISBN: 978-1-118-21506-7, John Wiley & Sons, pp. 1-208.

Asseng, S., Ewert, F., Martre, P., Rötter, R. P., Lobell, D. B., Cammarano, B. D., Kimball, A., Ottman, M. J., Wall, G. W., White, J. W., Reynolds, M. P., Alderman, P. D. Prasad, P.V. V., Aggarwal, P. K., Anothai, J., Basso, B., Biernath, C., Challinor, A. J., De Sanctis, G., Doltra, J., Fereres, E., M. Garcia-Vila, Gayler, S., Hoogenboom, G., Hunt, L. A. (2015). Rising temperatures reduce global wheat production. *Nature Climate Change* 5**(2)**:143-147.

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., & Brisson, N. (2013). Uncertainty in simulating wheat yields under climate change. *Nature Climate Change* 3**(9)**:827-832.

Asseng, S., Foster, I. A. N., & Turner, N. C. (2011). The impact of temperature variability on wheat yields. *Global Change Biology* 17 **(2)**: 997-1012.

Attavanich, W., & McCarl, B. A. (2014). How is CO_2 affecting yields and technological progress? A statistical analysis. *Climatic change* 124 **(4)**:747-762.

Attri, S. D., Singh, K. K., & Mall, R. K. (2011). Simulation of growth and yield attributes of wheat genotypes under changing climate in recent years in India. In *Challenges and Opportunities in Agrometeorology,* pp. 221-234.

Attri, S.D & Rathore, L.S. (2003). Simulation of impact of projected climate change on wheat in India. *International journal of climatology* 23 **(6)**: 693-705.

Balmaseda, M.A., Trenberth, K.E., Källén, E. (2013). Distinctive climate signals in reanalysis of global ocean heat content. *Geophysical Research Letters* 40 **(9)**:1754-1759.

Batchelor, W. D., Paz, J. O., Thorp, K. R., & Mulla, D. J. (2004). Development and evaluation of a decision support system for precision agriculture. *In Proceedings of the 7th International Conference on Precision Agriculture and Other Precision Resources Management*, Hyatt Regency, Minneapolis, MN, USA, 25-28 July, 2004. (pp. 2005-2109). Precision Agriculture Center, University of Minnesota, Department of Soil, Water and Climate.

Batts, G.R., Morison, J.I.L., Ellis, R.H., Hadley, P. and Wheeler, T.R. (1998). Effects of CO_2 and temperature on growth and yield of crops of winter wheat over four seasons. *European Journal of Agronomy* 7 **(1-3)**:43-52.

Behera, U.K., Saiprasad, S.V. and Dass, A. (2015). Response of wheat varieties to different nitrogen levels under dryland conditions in Vertisols of Central India. *Annals of Agricultural Research, New Series* 36 **(2)**: 152-159.

Bencze, S., Veisz, O. and Bedő, Z. (2004). Effects of high atmospheric CO_2 and heat stress on phytomass, yield and grain quality of winter wheat. *Cereal Research Communications*, 32 **(1)**:75-82.

Benlloch-Gonzalez, M., Bochicchio, R., Berger, J., Bramley, H., & Palta, J. A. (2014). High temperature reduces the positive effect of elevated CO_2 on wheat root system growth. *Field Crops Research* **165**:71-79.

Bhagat, R. M., Singh, S., Sood, C., Rana, R. S., Kalia, V., Pradhan, S. & Shrestha, B. (2009). Land suitability analysis for cereal production in Himachal Pradesh (India) using Geographical Information System. *Journal of the Indian Society of Remote Sensing*, 37 **(2)**: 233-240.

Biernath, Christian, Bittner, S., Klein, C., Gayler, S., Hentschel, R., Hoffmann, P., Hogy, P. Fangmeier, A. and Priesack E. (2013) Modeling acclimation of leaf photosynthesis to atmospheric CO_2 enrichment. *European Journal of Agronomy* **48**: 74-87.

Bishnoi, O. P., Singh, S. and Ram Niwas (1995). Effect of temperature on phenological development of wheat *(Triticum aestivum). Indian Journal of Agricultural Science* **65**: 211-14.

Biswas, D. K., Xu, H., Li, Y. G., Ma, B. L., & Jiang, G. M. (2013). Modification of photosynthesis and growth responses to elevated CO_2 by ozone in two cultivars of winter wheat with different years of release. *Journal of experimental botany*, doi: 10.1093/jxb/ert005.

Blumenthal, C., Rawson, H.M. and McKenzie, E. (1996). Changes in Wheat Grain Quality Due to Doubling the Level of Atmospheric CO2. *Cereal Chemistry* 73 **(6)**:762-766.

Bouyoucos G J. 1962. Hydrometer method improved for making particle size analysis of soils. *Agronomy Journal* **54**: 464–465.

Bouyoucos, C.J. (1936). Direction of making mechanical analysis of soil by hydrometer method. *Soil Science* **42**: 225-228.

Bradford, M. M. (1976). A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. *Analytical biochemistry*, **72(1-2)**: 248-254.

Brassard, J. P., & Singh, B. (2008). Impacts of climate change and CO_2 increase on agricultural production and adaptation options for Southern Quebec, Canada. *Mitigation and Adaptation Strategies for Global Change* **13(3)**: 241-265.

Bremner, J. M. (1960). Determination of nitrogen in soil by the Kjeldahl method. *The Journal of Agricultural Science*, *55*(1), 11-33.

Bremner, J. M. (1965). Total nitrogen. *Methods of soil analysis. Part 2. Chemical and microbiological properties*: 1149-1178.

Brown, R. A., & Rosenberg, N. J. (1999). Climate change impacts on the potential productivity of corn and winter wheat in their primary United States growing regions. *Climatic Change* **41 (1)**:73-107.

Bunce, J. A. (2013). Effects of pulses of elevated carbon dioxide concentration on stomatal conductance and photosynthesis in wheat and rice. *Physiologia plantarum* 149 **(2)**: 214-221.

Busch, F. A., Sage, T. L., Cousins, A. B. & Sage, R. F. (2013). C_3 plants enhance rates of photosynthesis by reassimilating photorespired and respired CO_2. *Plant, Cell & Environment* 36 **(1):** 200-212.

Cai, C., Yin, X., He, S., Jiang, W., Si, C., Struik, P. C., ... & Pan, G. (2016). Responses of wheat and rice to factorial combinations of ambient and elevated CO2 and temperature in FACE experiments. *Global change biology*, *22*(**2**), 856-874.

Cai, C., Yin, X., He, S., Jiang, W., Si, C., Struik, P.C., Luo, W., Li, G., Xie, Y., Xiong, Y. (2015). Responses of wheat and rice to factorial combinations of ambient and elevated CO_2 and temperature in FACE experiments. *Global change biology* 22 **(2)**:856-874.

Callaghan, T. V., Johansson, M., Brown, R. D., Groisman, P. Y., Labba, N., Radionov, V., Barry, R. G., Bulygina, O. N., Essery, R. L. & Frolov, D. (2011). The changing face of Arctic snow cover: A synthesis of observed and projected changes. *Ambio*, 40 **(1)**: 17-31.

Cannell, M. G. R., & Thornley, J. H. M. (1998). Temperature and CO_2 responses of leaf and canopy photosynthesis: a clarification using the non-rectangular hyperbola model of photosynthesis. *Annals of Botany*, 82 **(6)**: 883-892.

Challinor, A., Wheeler, T., Craufurd, P., Slingo, J., Grimes, D. (2004). Design and optimisation of a large-area process-based model for annual crops. *Agricultural and forest meteorology,* 124 **(1)**: 99-120.

Chavas, D. R., Izaurralde, R. C., Thomson, A. M., & Gao, X. (2009). Long-term climate change impacts on agricultural productivity in eastern China. *Agricultural and Forest Meteorology* 149 **(6):** 1118-1128.

Cho, J., & Oki, T. (2012). Application of temperature, water stress, CO_2 in rice growth models. *Rice* 5 **(1):** 1.

Choudhary, A.K., Bana, R.S. Pooniya, V., Dass, A. and Rana, K.S. (2014) Agricultural production, food security and climate change: A dialogue on challenges and mitigation strategies. *The IFFCO Foundation Bulletin,* 2**(2)**: 1-11.

Cline, W.R. (2007). *Global warming and agriculture: Impact estimates by country*. Printed by- Peter G Peterson Institute for international economics, Washington DC, USA., 201 pp. ISBN 978-0-88132-403-7-52195.

Colour, M. (1991). Munsell soil colour charts. *Geoderma,* 48 **(199)**: 199.

Conway, G. R., & Barbier, E. B. (2013). *After the green revolution: sustainable agriculture for development*. Routledge.

Conway, G.R. and Barbier, E.B. (2013) After the Green Revolution: Sustainable Agriculture for Development. Rout- ledge, London.

Cotrufo, M.F., Ineson, P. and Scott, A.(1998). Elevated CO_2 reduces the nitrogen concentration of plant tissues. *Global Change Biology,* 4**(1)**:43-54.

Crosson, P. (1991). After the green revolution: Sustainable agriculture for development: Gordon R. Convay and Edward B. Barbier. Earthscan Publications, London, 1990, 205 pp. ISBN 1-85383-035-6.

Cuculeanu, V., Marica, A., & Simota, C. (1999). Climate change impact on agricultural crops and adaptation options in Romania. *Climate Research,* 12 **(2-3)**:153-160.

Dahal, K., Weraduwage, S. M., Kane, K., Rauf, S. A., Leonardos, E. D., Gadapati, W. & Micallef, M. C. (2014). Enhancing biomass production and yield by maintaining enhanced capacity for CO_2 uptake in response to elevated CO_2. *Canadian Journal of Plant Science* 94 **(6)**: 1075-1083.

Dass, A., Nain, A. S., Sudhishri, S., & Chandra, S. (2012). Simulation of maturity duration and productivity of two rice varieties under system of rice intensification using DSSAT v 4.5/CERES-Rice model. *Journal of Agrometeorology* 14 **(1)**: 26-30.

Deepak, S.S. and Agrawal, M., (1999). Growth and yield responses of wheat plants to elevated levels of CO_2 and SO_2, singly and in combination. *Environmental Pollution***104 (3)**:411-419.

Deryng, D., Conway, D., Ramankutty, N., Price, J., & Warren, R. (2014). Global crop yield response to extreme heat stress under multiple climate change futures. *Environmental Research Letters* **9 (3)**: 034011.

Deryng, D., Elliott, J., Folberth, C., Müller, C., Pugh, T. A., Boote, K. J., ...& Khabarov, N. (2016). Regional disparities in the beneficial effects of rising CO_2 concentrations on crop water productivity. *Nature Climate Change*, *6* (**4**): 1-8.

DES (2014). Agricultural Statistics At a Glance 2014, Published by-Government of India Ministry of Agriculture Department of Agriculture & Cooperation Directorate of Economics & Statistics. ISBN-13: 978-0-19-945965-0, pp. 1-482.

Dietterich LH, Zanobetti A, Kloog I, Huybers P, Leakey AD, Bloom AJ, Carlisle E, Fernando N, Fitzgerald G, Hasegawa T, Holbrook NM. (2015) Impacts of elevated atmospheric CO_2 on nutrient content of important food crops. *Scientific data*. 2:150036, pp.1-6 | DOI: 10.1038/sdata.2015.36.

Dijkstra, P., Schapendonk, A.D., Groenwold, K.O., Jansen, M. and Van De Geijn, S.C. (1999). Seasonal changes in the response of winter wheat to elevated atmospheric CO_2 concentration grown in Open-Top Chambers and field tracking enclosures. *Global Change Biology* 5 **(5)**: 563-576.

Donatelli, M., Russell, G., Rizzoli, A.E., Acutis, M., Adam, M., Athanasiadis, I.N., Balderacchi, M., Bechini, L., Belhouchette, H., Bellocchi, G. (2010). A component-based framework for simulating agricultural production and externalities. In *Environmental and Agricultural Modelling* (pp. 63-108). Springer Netherlands.

Dong, C., Shao, L., Wang, M., Liu, G., Liu, H., Xie, B., Li, B., Fu, Y. & Liu, H. (2016). Wheat Carbon Dioxide Responses in Space Simulations Conducted at the Chinese Lunar Palace-1. *Agronomy Journal,* 108 **(1)**: 32-38.

Drake B.G, Gonzalez Meler MA, Long S.P. (1997). More efficient plants: A consequence of rising atmospheric CO2? *Annual review of plant physiology and plant molecular biology,* **48**:609-639.

Dubey, S. K., Tripathi, S. K. & Pranuthi, G. (2015b). 21st century climate change scenario of Haridwar district in Uttarakhand. In: *Proceedings of national seminar on Water Management and Climate smart Agriculture*, Editted by Subbaiah, R and Prajapati, **2**:1-9.

Dubey, S., Tripathi, S. & Pranuthi, G. (2015a). Effect of Elevated CO_2 on Wheat Crop: Mechanism and Impact. *Critical Reviews in Environmental Science and Technology*, 45 **(21)**: 2283-2304.

Dubey, S., Tripathi, S., Pranuthi, G. & Yadav, R. (2014). Impact of projected climate change on wheat varieties in Uttarakhand, India. *Journal of Agrometeorology,* 16 **(1)**: 26.

Dubois, M., Gilles, K. A., Hamilton, J. K., Rebers, P. A. T., & Smith, F. (1956). Colorimetric method for determination of sugars and related substances. *Analytical chemistry* 28 **(3):** 350-356.

Erda, L., Wei, X., Hui, J., Yinlong, X., Yue, L., Liping, B., & Liyong, X. (2005). Climate change impacts on crop yield and quality with CO_2 fertilization in China. *Philosophical Transactions of the Royal Society B: Biological Sciences* 360 **(1463):** 2149-2154.

Estes, L. D., Bradley, B. A., Beukes, H., Hole, D. G., Lau, M., Oppenheimer, M., Schulze G.,R. & Turner, W. R. (2013). Comparing mechanistic and empirical model projections of crop suitability and productivity: implications for ecological forecasting. *Global Ecology and Biogeography,* 22 **(8)**: 1007-1018.

Ewert, F., Rodriguez, D., Jamieson, P., Semenov, M. A., Mitchell, R. A. C., Goudriaan, J., & Weigel, H. J. (2002). Effects of elevated CO_2 and drought on wheat: testing crop simulation models for different experimental and climatic conditions. *Agriculture, Ecosystems & Environment,* 93**(1)**: 249-266.

Fan, M., Shen, J., Yuan, L., Jiang, R., Chen, X., Davies, W. J., & Zhang, F. (2011). Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. *Journal of experimental botany*, *63*(**1**), 13-24.

Fangmeier, A., De Temmerman, L., Mortensen, L., Kemp, K., Burke, J., Mitchell, R., Van Oijen, M. and Weigel, H.J. (1999). Effects on nutrients and on grain quality in spring wheat crops grown under elevated CO_2 concentrations and stress conditions in the European, multiple-site experiment 'ESPACE-wheat'. *European Journal of Agronomy*, 10 **(3)**: 215-229.

Fangmeier, A., Grüters, U., Hogy, P., Vermehren, B. and Jäger, H.J. (1997). Effects of elevated CO_2, nitrogen supply and tropospheric ozone on spring wheat—II. Nutrients (N, P, K, S, Ca, Mg, Fe, Mn, Zn). *Environmental Pollution,* 96 **(1)**: 43-59.

FAOSTAT (2014). http://faostat3.fao.org [Sat Apr 09 11:18:24 CEST 2016].

Fernando N, Panozzo J, Tausz M, Norton RM, Fitzgerald GJ, Myers S, Nicolas ME, Seneweera S. (2014a) Intra-specific variation of wheat grain quality in response to elevated [CO_2] at two sowing times under rain-fed and irrigation treatments. *Journal of Cereal Science,* 59: 137-144

Fernando N, Panozzo J, Tausz M, Norton RM, Neumann N, Fitzgerald GJ, Seneweera S. (2014b) Elevated CO_2 alters grain quality of two bread wheat cultivars grown under different environmental conditions. *Agriculture, Ecosystems & Environment,* **185**: 24-33.

Fernando, N., Panozzo, J., Tausz, M., Norton, R., Fitzgerald, G. and Seneweera, S. (2012). Rising atmospheric CO_2 concentration affects mineral nutrient and protein concentration of wheat grain. *Food Chemistry,* 133 **(4)**:1307-1311.

Fisher, R. A. (1926). The arrangement of field experiments. *Journal of the Ministry of Agriculture of Great Britain,* **33:** 503–513.

Fox, D.G. (1981). Judging air quality model performance: a summary of the AMS workshop on dispersion models performance. *Bulletin of the American Meteorological Society,* **62**:599-609.

Franks, P. J., & Beerling, D. J. (2009). Maximum leaf conductance driven by CO_2 effects on stomatal size and density over geologic time. *Proceedings of the National Academy of Sciences* 106 **(25):** 10343-10347.

Franks, P. J., Adams, M. A., Amthor, J. S., Barbour, M. M., Berry, J. A., Ellsworth, D. S., Farquhar, G. D., Ghannoum, O., Lloyd, J. & McDowell, N. (2013). Sensitivity of plants to changing atmospheric CO_2 concentration: from the geological past to the next century. *New Phytologist,* 197 **(4)**: 1077-1094.

Gangaiah, B., Singh, H., Shiva Kumar, B.G., and Dass, A. (2014) Direct and residual effects of nitrogen and phosphorus fertilization of *Dhaincha* (*Sesbania aculeata*) seed crop on succeeding wheat (*Triticum aestivum*) at two levels of N fertilization. *Journal of Agri-Food and Applied Sciences,* 2 **(2)**: 31-38.

Ghosh, K., Balasubramanian, R., Bandopadhyay, S., Chattopadhyay, N., Singh, K. K., & Rathore, L. S. (2014). Development of crop yield forecast models under FASAL-a case study of kharif rice in West Bengal. *Journal of Agrometeorology,* 16 **(1)**:1-6.

Gifford, R.M., Barrett, D.J. and Lutze, J.L. (2000). The effects of elevated [CO_2] on the C: N and C: P mass ratios of plant tissues. *Plant and Soil,* 224 **(1)**:1-14.

Gijsman, A.J., Hoogenboom, G., Parton, W.J., Kerridge, P.C. (2002). Modifying DSSAT for low-input agricultural systems, using a soil organic matter/residue module from CENTURY. *Agronomy Journal*, 94 (**3**), 462/474.

Hasegawa, T., Sakai, H., Tokida, T., Nakamura, H., Zhu, C., Usui, Y., Yoshimoto, M., Fukuoka, M., Wakatsuki, H., Katayanagi, N. and Matsunami, T. (2013). Rice cultivar responses to elevated CO_2 at two free-air CO_2 enrichment (FACE) sites in Japan. *Functional Plant Biology,* 40 **(2)**:148-159.

Hawkesford, M. J., Araus, J. L., Park, R., Calderini, D., Miralles, D., Shen, T., Zhang, J. & Parry, M. A. (2013). Prospects of doubling global wheat yields. *Food and Energy Security,* 2 **(1)**: 34-48.

Hogy, P. and Fangmeier, A. (2008). Effects of elevated atmospheric CO_2 on grain quality of wheat. *Journal of Cereal Science*, 48 **(3)**:580-591.

Hogy, P., Brunnbauer, M., Koehler, P., Schwadorf, K., Breuer, J., Franzaring, J., Zhunusbayeva, D. and Fangmeier, A. (2013). Grain quality characteristics of spring wheat (Triticum aestivum) as affected by free-air CO_2 enrichment. *Environmental and Experimental Botany,* **88**:11-18.

Hogy, P., C. Zörb, G. Langenkämper, T. Betsche, and A. Fangmeier. (2009a) Atmospheric CO_2 enrichment changes the wheat grain proteome. *Journal of Cereal Science,* 50**(2)**: 248-254.

Hogy, P., Keck, M., Niehaus, K., Franzaring, J. and Fangmeier, A. (2010). Effects of atmospheric CO_2 enrichment on biomass, yield and low molecular weight metabolites in wheat grain. *Journal of Cereal Science,* 52 **(2)**:215-220.

Hogy, P., Wieser, H., Köhler, P., Schwadorf, K., Breuer, J., Franzaring, J., & Fangmeier, A. (2009b). Effects of elevated CO_2 on grain yield and quality of wheat: results from a 3-year free-air CO2 enrichment experiment. *Plant Biology,* 11 **(s1)**: 60-69.

Holzworth, D. P., Snow, V., Janssen, S., Athanasiadis, I. N., Donatelli, M., Hoogenboom, G., White, J., & Thorburn, P. (2014). Agricultural production systems modelling and software: current status and future prospects. *Environmental Modelling & Software,* 30 **(1)**:e11- e23.

Holzworth, D. P., Snow, V., Janssen, S., Athanasiadis, I. N., Donatelli, M., Hoogenboom, G. & Thorburn, P. (2015). Agricultural production systems modelling and software: current status and future prospects. *Environmental Modelling & Software*, **72:** 276-286.

Hoogenboom, G., Jones, J. W., Wilkens, P. W., Porter, C. H., Batchelor, W. D., Hunt, L. A., & Gijsman, A. J. (2004). Decision support system for agrotechnology transfer version 4.0. University of Hawaii, Honolulu, HI (CD-ROM).

Idso, S.B. and Idso, K.E. (2001). Effects of atmospheric CO_2 enrichment on plant constituents related to animal and human health. *Environmental and Experimental Botany,* 45 **(2)**:179-199.

Iglesias, A. (2006). Use of DSSAT models for climate change impact assessment: Calibration and validation of CERES-Wheat and CERES Maize in Spain. CGE Hands-on Training Workshop on V&A Assessment of the Asia and the Pacific Region Jakarta, 20-24 March 2006-03-21

Islam, A., Ahuja, L. R., Garcia, L. A., Ma, L., Saseendran, S. A.,& Trout, T. J. (2012). Modeling the impacts of climate change on irrigated corn production in the Central Great Plains. *Agricultural Water Management,* 110:94-108.

Jackson, M.L. (1973). Soil Chemical Analysis. Prentice Hall of India Pvt. Ltd., New Delhi. 498 p.

Jia, X., Liu, T., Zhao, Y., He, Y., & Yang, M. (2016). Elevated atmospheric CO_2 affected photosynthetic products in wheat seedlings and biological activity in rhizosphere soil under cadmium stress. *Environmental Science and Pollution Research*, 23 **(1)**:514-526.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T. (2003). The DSSAT cropping system model. *European Journal of Agronomy,*18 **(3)**:235-265.

Joshi, M., Hawkins, E., Sutton, R., Lowe, J. & Frame, D. (2011). Projections of when temperature change will exceed 2 ^{0}C above pre-industrial levels. *Nature Climate Change* 1**(8)**: 407-412.

K. Yamanka and F. Fryer (2001) Measurement of Macro and Trace element in plant digest using the 7500c ICP-MS System. *Agilent technologies*. pp. 1-6.

Kaddour, A. A., & Fuller, M. P. (2004). The effect of elevated CO_2 and drought on the vegetative growth and development of Durum wheat (Triticum durum Desf.) cultivars. *Cereal Research Communications*: 225-232.

Kant, S., Seneweera, S., Rodin, J., Materne, M., Burch, D., Rothstein, S. J., & Spangenberg, G. (2012). Improving yield potential in crops under elevated CO_2: integrating the photosynthetic and nitrogen utilization efficiencies. *Frontiers in plant science* **3**:162-165.

Karen and Norton, Robert M. and Fitzgerald, Glenn J. andTausz, Michael and Seneweera, Saman (2015) Intraspecific variation in leaf growth of wheat (Triticum aestivum) under Australian Grain Free Air CO_2 Enrichment (AGFACE): Is it regulated through carbon and/or nitrogen supply? *Functional Plant Biology,* 42 **(3)**:299-308. ISSN 1445-4408.

Keenan, T. F., Prentice, I. C., Canadell, J. G., Williams, C. A., Wang, H., Raupach, M., & Collatz, G. J. (2016). Recent pause in the growth rate of atmospheric CO_2 due to enhanced terrestrial carbon uptake. *Nature communications*, 7.

Khichar, M. L., Niwas, R., & Behl, R. K. (2008). Impact of agro meteorological variables on nitrogen uptake and crude protein content of wheat under different planting and sowing environments. *Tropics,* 17**(3)**:185-191.

Kimball, B. A. (1983). Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observations. *Agronomy Journal,* 75**(5)**: 779-788.

Kimball, B. A., Mauney, J. R., Nakayama, F. S., & Idso, S. B. (1993). Effects of elevated CO_2 and climate variables on plants. *Journal of Soil and Water Conservation*, 48(**1**), 9-14.

Kimball, B.A., Kobayashi, K., Bindi, M. (2002). Responses of agricultural crops to free air CO_2 enrichment. *Advances in Agronomy.* **77**:293–368.

Kimball, B.A., Morris, C.F., Pinter, P.J., Wall, G.W., Hunsaker, D.J., Adamsen, F.J., LaMorte, R.L., Leavitt, S.W., Thompson, T.L., Matthias, A.D. and Brooks, T.J., (2001). Elevated CO_2, drought and soil nitrogen effects on wheat grain quality. *New Phytologist* 150**(2)**: 295-303.

Kjeldahl, J. (1883). A new method for the determination of nitrogen in organic matter. *Analytical Chemistry* 22**(1):**366-382.

Ko, J., Ahuja, L., Kimball, B., Saseendran, S.A., Ma, L., Green, T. R., & Bader, D. A. (2010). Simulation of free air CO_2 enriched wheat growth and interactions with water, nitrogen, and temperature. *Agricultural and Forest Meteorology,* 150**(10)**: 1331-1346.

Kumar, N., Kumar, S., & Nain, A. S. (2014). Response of CERES-wheat and CROPGRO-urd model (DSSAT model v 4.5) for tarai region of Uttarakhand. *Mausam,* 65**(1)**: 109-114.

Ladha, J. K., Pathak, H., Tirol-Padre, A., Dawe, D. & Gupta, R. K. (2003). Productivity trends in intensive rice–wheat cropping systems in Asia. Improving the Productivity and Sustainability of Rice–Wheat Systems: Issues and Impacts, *ASA Special Publication,* **65**: 45-76.

Lal, M., Singh, K.K., Rathore, L.S., Srinivasan, G. and Saseendran, S.A. (1998). Vulnerability of rice and wheat yields in NW India to future changes in climate. *Agricultural and forest meteorology,* 89**(2)**:101-114.

Lawlor, D. & Mitchell, R. (1991). The effects of increasing CO_2 on crop photosynthesis and productivity: a review of field studies. *Plant, Cell & Environment,* 14 **(8)**: 807-818.

Leakey, A. D., Ainsworth, E. A., Bernacchi, C. J., Rogers, A., Long, S. P. & Ort, D. R. (2009). Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of experimental botany,* 60 **(10)**: 2859-2876.

Leakey, A. D., Ainsworth, E. A., Bernacchi, C. J., Rogers, A., Long, S. P., & Ort, D. R. (2009). Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of experimental botany*, *60*(**10**): 2859-2876.

Legates, D. R., & McCabe, G. J. (1999). Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research,* 35 **(1):** 233-241.

Li , Q., Liang, W., Jiang, Y., Shi, Y., Zhu, J. and Neher, D.A., (2007). Effect of elevated CO_2 and N fertilisation on soil nematode abundance and diversity in a wheat field. *Applied Soil Ecology,* 36 **(1)**:63-69.

Liu, B., Asseng, S., Liu, L., Tang, L., Cao, W., & Zhu, Y. (2016). Testing the responses of four wheat crop models to heat stress at anthesis and grain filling. *Global change biology*, *22*(**5**), 1890-1903.

Liu, H. L., Yang, J. Y., Tan, C. S., Drury, C. F., Reynolds, W. D., Zhang, T. Q., & Hoogenboom, G. (2011). Simulating water content, crop yield and nitrate-N loss under free and controlled tile drainage with subsurface irrigation using the DSSAT model. *Agricultural Water Management,* 98**(6)**: 1105-1111.

Loague, K., and R.E. Green. 1991. Statistical and graphical methods for evaluating solute transport models: overview and application. *Journal of Contaminant Hydrology,* **7**:51-73.

Lobell, D. B., Schlenker, W. & Costa-Roberts, J. (2011). Climate trends and global crop production since. 1980. *Science,* 333 **(6042)**: 616-620.

Lobell, D. B., Sibley, A. & Ortiz-Monasterio, J. I. (2012). Extreme heat effects on wheat senescence in India. *Nature Climate Change,* 2**(3)**: 186-189.

Loladze, I. (2002). Rising atmospheric CO_2 and human nutrition: toward globally imbalanced plant stoichiometry. *Trends in Ecology & Evolution,* 17 **(10)**:457-461.

Long, S. P., Ainsworth, E. A., Leakey, A. D., Nösberger, J., & Ort, D. R. (2006). Food for thought: lower-than-expected crop yield stimulation with rising CO_2 concentrations. *Science*, 312 **(5782)**: 1918-1921.

Long, S. P., Ainsworth, E. A., Rogers, A., & Ort, D. R. (2004). Rising atmospheric carbon dioxide: plants FACE the Future. *Annual Review of Plant Biology,* **55**: 591-628.

Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Morgan, P.B. (2005). Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggests recent models may have overestimated future yields. *Philosophical Transactions of the Royal Society of London,* **360**:2011–2020.

Ludwig, F., & Asseng, S. (2006). Climate change impacts on wheat production in a Mediterranean environment in Western Australia. *Agricultural Systems,* 90 **(1)**:159-179.

Ludwig, F., Milroy, S. P., &Asseng, S. (2009). Impacts of recent climate change on wheat production systems in Western Australia. *Climatic Change,* 92 **(3-4)**:495-517.

Ma, L., Ahuja, L. R., Trout, T. J., Nolan, B. T., & Malone, R. W. (2016). Simulating Maize Yield and Biomass with Spatial Variability of Soil Field Capacity. *Agronomy Journal,* 108 **(1)**: 171-184.

Mall R K, Neha S., Hema Singh (2016): Evaluation of CERES-Wheat model for different wheat cultivars. *Journal of Agrometeorology,* 18 **(1)**: 24-36

Mall, R. K., Gupta, B. R. D., & Singh, K. K. (2001). Application of SPAW model parameters-optimum sowing date and water stress to explain wheat yield variability. *Mausam,* 52 **(3)**:567-574.

Malone, R., Dharmasri, C., Hatfield, J., &Ahuja, L. (2015). Know your community: Model applications in field research. *Crops, Soils, Agronomy News* 60 **(1)**:32-32.

Marchal, V., Dellink, R., Van Vuuren, D., Clapp, C., Chateau, J., Magné, B. & van Vliet, J. (2011). OECD Environmental Outlook to 2050. Organization for Economic Co-operation and Development. ISBN978-92-64-12216-1, pp.1-340. DOI:10.1787/9789264122246-en.

Masle, J. (2000). The effects of elevated CO_2 concentrations on cell division rates, growth patterns, and blade anatomy in young wheat plants are modulated by factors related to leaf position, vernalization, and genotype. *Plant Physiology,* 122 **(4):**1399-1416.

Masle, J. (2000). The effects of elevated CO_2 concentrations on cell division rates, growth patterns, and blade anatomy in young wheat plants are modulated by factors related to leaf position, vernalization, and genotype. *Plant Physiology*, 122(**4**): 1399-1416.

Mayeux, H., Johnson, H., Polley, W., & Malone, S. (1997). Yield of wheat across a sub ambient carbon dioxide gradient. *Global Change Biology,* 3 **(3)**: 269-278.

Meehl, G.A., Stocker, T.F., Cllins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., Zhao, Z.-C. (2007). Global climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z.,Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Annual Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York.

Meena, R. K., Vashisth, A., Aggarwal, P., Bhattacharyya, R., DAS, T., & Singh, S. D. (2015) Growth and Yield of Maize Crop under different Conservation Practices in Semi-Arid Region of India. *Journal of Agroecology and Natural Resource Management,* 2 **(4)**: 264-267.

Mishra, A.K., Rai, R. and Agrawal, S.B., (2013). Differential response of dwarf and tall tropical wheat cultivars to elevated ozone with and without carbon dioxide enrichment: growth, yield and grain quality. *Field Crops Research,* **145**:21-32.

Moore B.D., Cheng S.H., Rice J., Seemann J.R. (1998) Sucrose cycling, Rubisco expression, and prediction of photosynthetic acclimation to elevated atmospheric CO_2. *Plant, Cell and Environment,* **21:** 905–915.

Moore B.D., Cheng S.H., Sims D., Seemann J.R. (1999) The biochemical and molecular basis for photosynthetic acclimation to elevated atmospheric CO_2. *Plant, Cell and Environment,* **22**: 567–582.

Mukherjee, J., Das, D., Sehgal, V., Vashisth, A., Singh, R., & Barari, S. (2014). South west monsoon and food grain production of India. *Journal of Agricultural Physics,* 14 **(1)**:73-79.

Mulchi, C. L., Slaughter, L., Saleem, M., Lee, E. H., Pausch, R., & Rowland, R. (1992). Growth and physiological characteristics of soybean in open-top chambers in response to ozone and increased atmospheric CO_2. *Agriculture, Ecosystems & Environment* 38**(1-2)**: 107-118.

Mulholland, B. J., Craigon, J., Black, C. R., Colls, J. J., Atherton, J., & Landon, G. (1997). Effects of elevated carbon dioxide and ozone on the growth and yield of spring wheat (Triticum aestivum L.). *Journal of Experimental Botany* 48**(1)**: 113-122.

Myers, S. S., Wessells, K. R., Kloog, I., Zanobetti, A., & Schwartz, J. (2015). Effect of increased concentrations of atmospheric carbon dioxide on the global threat of zinc deficiency: a modelling study. *The Lancet Global Health* 3**(10)**: e639-e645.

Myers, S. S., Zanobetti, A., Kloog, I., Huybers, P., Leakey, A. D., Bloom, A., Carlisle, E., Dietterich, L. H., Fitzgerald, G., Hasegawa, T., Schwartz, J., Seneweera, S., Tausz, M. & Usui, Y. (2014). Rising CO_2 threatens human nutrition. *Nature,* 510 **(7503)**: 139.

Nicholls, R. J., Marinova, N., Lowe, J. A., Brown, S., Vellinga, P., De Gusmao, D., Hinkel, J. & Tol, R. S. (2011). Sea-level rise and its possible impacts given a 'beyond 4 C world'in the twenty-first century. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences,* 369 **(1934)**: 161-181.

Niu, L., Feng, S., Ding, W., & Li, G. (2016). Influence of Speed and Rainfall on Large-Scale Wheat Lodging from 2007 to 2014 in China. *PloS one*, 11(**7**), e0157677.

Niwas, R. & Khichar, M. (2016) Managing impact of climatic vagaries on the productivity of wheat and mustard in India. *Mausam,* 67 **(1)**: 205-222.

O'Leary, G. J., Christy, B., Nuttall, J., Huth, N., Cammarano, D., Stöckle, C., & Farre-Codina, I. (2015). Response of wheat growth, grain yield and water use to elevated CO_2 under a Free-Air CO_2 Enrichment (FACE) experiment and modelling in a semi-arid environment. Global change biology 21**(7)**: 2670-2686.

Olsen, S.R.; Cole, V.C.; Watnobe, F.S. and Dean, L.A. (1954). Estimation of available phosphorus in soil by extraction with sodium bicarbonate. Cire. U.S. Deptt. Ag., 939.

Olsson, G. (2015). Water and energy: threats and opportunities *pp.*77. IWA publishing.

Pal, M., Rao, L. S., Jain, V., Srivastava, A. C., Pandey, R., Raj, A., & Singh, K. P. (2005). Effects of elevated CO_2 and nitrogen on wheat growth and photosynthesis. *Biologia Plantarum* 49 **(3)**: 467-470.

Pal, M., Rao, L. S., Srivastava, A. C., Jain, V., & Sengupta, U. K. (2003). Impact of CO_2 enrichment and variable nitrogen supplies on composition and partitioning of essential nutrients of wheat. *Biologia Plantarum,* 47 **(2)**:227-231.

Pal, R. K., Segal, V. K., Mishra, A. K., Ghosh, K., Mohanty, U. C., & Rana, R. S. (2013). Application of seasonal temperature and rainfall forecast for wheat yield prediction for Palampur, Himachal Pradesh. *International Journal of Agriculture and Food Technology*, 4**(5)**:453-460.

Pal, R.K. and Murthy, N.S. (2010) Thermal requirements of wheat under different growing environments of Tarai Region (Uttarakhand). *ISPRS Archives,* 38 **(8)**:78-79.

Pal, R.K., Murthy, N.S. and R MMN (2012a) Evaluation of yield, dry matter accumulation and leaf area index in wheat (*Triticum aestivum L.*) genotypes as affected by different sowing environments. *Environment and Ecology,* 30 **(4A)**:1469-1473.

Pal, R.K., Murthy, N.S. and Rao, M.M.N. (2012b) The response of wheat to temperatures as simulated with CERES-wheat model in Tarai region. *Journal of Agrometeorology,* 14 **(2)**: 163-166.

Pal, R.K., Rao, M.M.N. and Murthy, N.S. (2012d) Relative temperature disparity and wheat yield as influenced by sowing environments and genotypes in Tarai region of Uttarakhand. *Environment and Ecology,* 31 **(2B)**: 979-983.

Pal, R.K., Rawat, K.S., Singh, J. and NS Murthy (2015a) Evaluation of CSM-CERES-wheat in simulating wheat yield and its attributes with different sowing environments in Tarai region of Uttarakhand. *Journal of Applied and Natural Science,* 7**(1)**:404-409.

Pandey, V. & Patel, H. (2012).Climate Change and Its Impact on Wheat and Maize Yield in Gujarat. In Challenges and Opportunities in Agrometeorology, 321-333: Springer.

Paroda, R. S., & Kumar, P. (2000). Food, production and demand in South Asia. *Agricultural Economics Research Review* **13 (1)**: 1-24.

Piikki, K., De Temmerman, L., Ojanperä, K., Danielsson, H. and Pleijel, H. (2008). The grain quality of spring wheat (Triticum aestivum L.) in relation to elevated ozone uptake and carbon dioxide exposure. *European Journal of Agronomy,* 28 **(3)**:245-254.

Pingali, P.L. (2012). Green revolution: impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences*, USA **109:** 12302–12308.

Pinter, P. J., Kimball, B. A., Wall, G. W., LaMorte, R. L., Hunsaker, D. J., Adamsen, F. J., ... & Nagy, J. (2000). Free-air CO_2 enrichment (FACE): blower effects on wheat canopy microclimate and plant development. *Agricultural and Forest Meteorology,* 103 **(4):** 319-333.

Pleijel, H. and Danielsson, H., (2009). Yield dilution of grain Zn in wheat grown in open-top chamber experiments with elevated CO_2 and O_3 exposure. *Journal of Cereal Science*50**(2)**:278-282.

Pleijel, H., Danielsson, H., Karlsson, G. P., Gelang, J., Karlsson, P. E., &Selldén, G. (2000). An ozone flux–response relationship for wheat.*Environmental Pollution,* 109 **(3)**: 453-462.

Poorter, H., Berkel, Y. V., Baxter, R., Hertog, J. D., Dijkstra, P., Gifford, R. M., & Wong, S. C. (1997). The effect of elevated CO_2 on the chemical composition and construction costs of leaves of 27 C_3 species. *Plant, Cell & Environment,* 20 **(4)**:472-482.

Pranuthi, G. (2016). *Effect of elevated CO_2 enrichment and climate change on ice crop through field and simulation study*. Ph.D. thesis submitted to Indian Institute of Technology Roorkee, Uttrakhand India, p.1-187.

Qiao, Y., Zhang, H., Dong, B., Shi, C., Li, Y., Zhai, H. and Liu, M., (2010). Effects of elevated CO2 concentration on growth and water use efficiency of winter wheat under two soil water regimes. *Agricultural Water Management,* 97**(11)**:1742-1748.

Rai, P., Chaturvedi, A.K., Shah, D., Viswanathan, C. and Pal, M., (2016). Elevated CO_2 enhances carbohydrate assimilation at flowering stage and seed yield in chickpea (Cicer arietinum). *Indian Journal of Plant Physiology*: 1-8.

Rana, R. S., Sood, R., Aditya, A., & Shekhar, J. (2013). Validation of medium range weather forecasts in sub-temperate and sub-humid climate of western Himalayas. *The Indian Journal of Agricultural Sciences,* 83**(12)**:217-222.

Rana, R.S, Bhosale, A.B., Sood, R., Sharma, R., Chander, N. (2011) Simulating impact of climate change on mustard (Brassica juncea) production in Himachal Pradesh. *Journal of Agrometeorology,* 13**(2)**: 104-109.

Rana, R.S. Singh, S., Chander, N., Sood, R., Sharma, R., and Aditya (2014) Impact of change in climate on mountain water resources of Himachal Pradesh. *Mausam,* 65 **(2)**:153-160.

Reich, P. B., Hobbie, S. E. & Lee, T. D. (2014). Plant growth enhancement by elevated CO_2 eliminated by joint water and nitrogen limitation. *Nature Geoscience,* 7**(12)**: 920-924.

Ritchie, J. T. (1972). Model for predicting evaporation from a row crop with incomplete cover. *Water resources research,* 8**(5)**: 1204-1213.

Ritchie, J., Otter, S. (1985). Description and performance of CERES-Wheat: a user-oriented wheat yield model. ARS-United States Department of Agriculture, Agricultural Research Service (USA). ARS, **38**:159-175.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A., Boote, K. J., Folberth, C., Glotter, M. & Khabarov, N. (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences,* 111 **(9)**: 3268-3273.

Samani, Z. (2000). Estimating solar radiation and evapotranspiration using minimum climatological data. Journal of Irrigation and Drainage Engineering **126 (4):** 265-267.

Saseendran, S. A., Nielsen, D. C., Ahuja, L. R., Ma, L., & Lyon, D. J. (2013). Simulated yield and profitability of five potential crops for intensifying the dryland wheat-fallow production system. *Agricultural water management*116:175-192.

Saseendran, S. A., Nielsen, D. C., Ma, L., Ahuja, L. R., & Halvorson, A. D. (2004). Modeling nitrogen management effects on winter wheat production using RZWQM and CERES-Wheat. *Agronomy Journal,* 96**(3)**:615-630.

Saseendran, S. A., Singh, K. K., Rathore, L. S., Singh, S. V., & Sinha, S. K. (2000). Effects of climate change on rice production in the tropical humid climate of Kerala, India. *Climatic Change*, *44*(4), 495-514.

Satapathy, S.S., Swain, D.K., Pasupalak, S. and Bhadoria, P.B.S., 2015. Effect of elevated [CO_2] and nutrient management on wet and dry season rice production in subtropical India. *The Crop Journal,* 3**(6)**:468-480.

Schmid, I., Franzaring, J., Müller, M., Brohon, N., Calvo, O. C., Hogy, P.,& Fangmeier, A. (2015). Effects of CO2 Enrichment and Drought on Photosynthesis, Growth and Yield of an Old and a Modern Barley Cultivar. *Journal of Agronomy and Crop Science,* 202**(2)**: 81–95.

Seneweera S, Makino A and T Mae (2005a) Response of rice to CO_2 enrichment: The relationship between photosynthesis and Ribulose-1,5-bisphosphate carboxylase/oxygenase. *Journal of Crop Improvement,* **13:** 31-53

Seneweera, S. P. & Conroy, J. P. (2005b). Enhanced leaf elongation rates of wheat at elevated CO_2: is it related to carbon and nitrogen dynamics within the growing leaf blade? *Environmental and Experimental Botany,* 54**(2)**: 174-181.

Shi, C.L., Jin, Z.Q., Ge, D.K., Su, G.L., 2001. Effects of climate change on crop yields and adaptation strategies in the middle and lower valleys of the Yangtze river. *Jiangsu Journal of Agriculture Science,* **17**:1-6.

Singh, K.K., Baxla, A., Mall, R., Singh, P., Balasubramanyam, R. & Garg, S. (2010a). Wheat yield prediction using CERES-Wheat model for decision support in agro-advisory. *Vayu mandal,* **5**: 97.

Singh, P. K., Rathore, L. S., Singh, K. K., Baxla, A. K. and Mall, R. K. (2010b), "Modeling the effect of planting date on Maize (Zea mays L.) Crop in Sabour region of Bihar using DSSATv3.5 crop simulation model", *Mausam,* 61**(1)**:75-80.

Singh, P. K., Singh, K. K., Baxla, A. K., & Rathore, L. S. (2015). Impact of Climatic Variability on Wheat Yield Predication using DSSAT v 4.5 (CERES-Wheat) Model for the different Agroclimatic zones in India. In *Climate Change Modelling, Planning and Policy for Agriculture* (pp. 45-55). Springer India.

Singh, P. K., Singh, K. K., Rathore, L. S., Baxla, A. K., Bhan, S. C., Gupta, A., Gohain, G. B. Balasubramanian, R., Singh, R. S., & Mall, R. K. (2016). Rice (Oryza sativa L.) yield gap using the CERES-rice model of climate variability for different agroclimatic zones of India. *Current science,* 110 **(3)**: 405.

Singh, S. D., Chakrabarti, B., Muralikrishna, K. S., Chaturvedi, A. K., Kumar, V., Mishra, S., & Harit, R. (2013). Yield response of important field crops to elevated air temperature and CO. *Indian Journal of Agricultural Sciences,* 83**(10)**:1009-1012.

Soimakallio, S. (2012). Assessing the uncertainties of climate policies and mitigation measures. Viewpoints on biofuel production, grid electricity consumption and differentiation of emission reduction commitments. VTT Technical Research Centre of Finland.*VTT Science,* **11**: 78 -80, ISBN 978-951-38-7469-8

Solomon et al. IPCC, (2007): Climate Change: The Physical Science Basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (*eds*.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 996.

Spalding M. (1994) Effects of altered carbon dioxide concentrations on gene expression. In *Plant Responses to the Gaseous Environment* (eds R. G.Aldrer & A. R.Wellburn), pp. 79–97. Chapman & Hall, London.

Sudhishri, S. and Dass, A. (2006) Thermal indices for major crops and prediction of growth and yield of finger millet in hilly southeastern Orissa state. *Journal of Agrometeorology*, 8**(2)**:186-191.

Sultana, H., Ali, N., Iqbal, M. M., & Khan, A. M. (2009). Vulnerability and adaptability of wheat production in different climatic zones of Pakistan under climate change scenarios. *Climatic Change,* 94**(1-2)**:123-142.

Taub, D.R., Miller, B. and Allen, H., (2008). Effects of elevated CO_2 on the protein concentration of food crops: a meta-analysis. *Global Change Biology,* 14**(3)**:565-575.

Teixeira, E.I., Fischer, G., van Velthuizen, H., Walter, C., Ewert, F. (2013). Global hot-spots of heat stress on agricultural crops due to climate change. *Agricultural and Forest Meteorology,* **170**:206-215.

Tester, R., Morrison, W., Ellis, R., Piggo, J., Batts, G., Wheeler, T., Morison, J., Hadley, P., Ledward, D. (1995). Effects of elevated growth temperature and carbon dioxide levels on some physicochemical properties of wheat starch. *Journal of Cereal Science,* 22**(1)**:63-71.

Thilakarathne CL, Tausz-Posch S, Cane K, Norton RM, Tausz M, Seneweera S (2013) Intraspecific variation in growth and yield response to elevated CO_2 in wheat depends on the differences of leaf mass per unit area. *Functional Plant Biology,* **40**: 185-193.

Thompson, B., & Cohen, M. J. (2015). Increased concentrations of atmospheric carbon dioxide and zinc deficiency. *The Lancet Global Health,* 3**(10)**:e585-e586.

Thornton, P.K., Ericksen, P.J., Herrero, M., Challinor, A.J. (2014). Climate variability and vulnerability to climate change: a review. *Global Change Biology,* 20 **(11)**: 3313-3328.

Timsina, J., & Humphreys, E. (2006). Performance of CERES-Rice and CERES-Wheat models in rice–wheat systems: a review. *Agricultural Systems,* 90 **(1)**: 5-31.

Trenberth, K. E. (2011). Changes in precipitation with climate change. *Climate Research,* 47 **(1)**: 1-43.

Tripathi S.K., Pranuthi, G. **Dubey**, **S.K.** Kumar G.V. and Mfwango L. (2013) Characterization of crop productivity using DSSAT for South West Uttarakhand India. In : Food and Environnent II by Brebbia C.A. and Popov, B., WIT Press Bostan UK. pp 113-122(doi:10.2495/FENVI30141).

Tripathi, S. K., Pranuthi, G. & Dubey, S. K. (2014). Climate Change Assessment Using Precis-RCM Data for Hardwar District of Uttarakhand. ASA, CSSA &SSSA International Annual Meeting, Grand Challanges and Great Solutions Nov. 02-05, 2014 at Long Beach, California.

Tripathi, S.K.; **Dubey, S.K.** and Pranuthi, G. (2015) PRECIS RCM based Climate change trend and DSSAT Forecasted Crop productivity in Hardwar district. Presented at the *TROPMET 2015 National Symposium on Weather & Climate Extremes* from Feb. 15-18, 2015 held at Chandigarh, India.

Tubiello, F. N., & Ewert, F. (2002). Simulating the effects of elevated CO_2 on crops: approaches and applications for climate change. *European journal of agronomy*, 18 **(1)**: 57-74.

UNFCCC, (2007). Impacts, vulnerabilities and adaptation in developing countries. In United Nations Framework Convention on Climate Change (UNFCCC), Climate Change Secretariat (UNFCCC) Martin-Luther-King-Strasse 853175 Bonn, Germany, pp.1-68.

Uprety, D.C., Dwivedi, N., Raj, A., Jaiswal, S., Paswan, G., Jain, V. and Maini, H.K. (2009). Study on the response of diploid, tetraploid and hexaploid species of wheat to the elevated CO_2. *Physiology and Molecular Biology of Plants,* 15**(2)**:161-168.

Usui, Y., Sakai, H., Tokida, T., Nakamura, H., Nakagawa, H., & Hasegawa, T. (2015). Rice grain yield and quality responses to free-air CO_2 enrichment combined with soil and water warming. *Global change biology,* 22**(3)**:1256-1270.

Vadez, Vincent, Jens D. Berger, Tom Warkentin, Asseng, S. Ratnakumar, P., Rao, K. P. C., Pooran, M., Sharma, H. C. (2012). Adaptation of grain legumes to climate change: A review. *Agronomy for Sustainable Development,* 32 **(1)**:31-44.

Vashisth, A., Chakravarty, N. V. K., Bhagavati, G., & Sharma, P. K. (2011). Effect of Weather Variability on Growth Characteristics of Brassica Crop. In: *Challenges and Opportunities in Agrometeorology* (pp. 519-528). Springer Berlin Heidelberg.

Vashisth, A., Choudary, M., Joshi, D. K., and Baloda, R. (2015) Pre Harvest Yield Forecast in Maize-Mustard Cropping System Under Semi-Arid Region Using Crop Simulation Model. *International Journal of Tropical Agriculture,* 33 **(2)***:*1059-1067.

Vashisth, A., Singh, R., & Choudary, M. (2014) Crop Yield Forecast at Different Growth Stage of Wheat Crop using Statistical Model under Semi-Arid Region. *Journal of Agroecology and Natural Resource Management,* 1**(1)**:1-3.

Wall, G. W., R. L. Garcia, B. A. Kimball, D. J. Hunsaker, P. J. Pinter, S. P. Long, C. P. Osborne Leavitt, S. W. (2006). Interactive effects of elevated carbon dioxide and drought on wheat. *Agronomy Journal,* 98**(2)**: 354-381.

Watson, E. R., Lapins, P., & Barron, R. J. W. (1976). Effect of waterlogging on the growth, grain and straw yield of wheat, barley and oats. *Australian Journal of Experimental Agriculture*, *16*(**78**), 114-122.

Wheeler, T., Batts, G., Ellis, R., Hadley, P. & Morison, J. (1996). Growth and yield of winter wheat (Triticum aestivum) crops in response to CO_2 and temperature. *The Journal of Agricultural Science,* 127**(01)**: 37-48.

Wheeler, T., von Braun, J. (2013). Climate change impacts on global food security. *Science*, 341**(6145)**: 508-513.

White, J. W., Hoogenboom, G., Kimball, B. A., & Wall, G. W. (2011). Methodologies for simulating impacts of climate change on crop production. *Field Crops Research,* 124 **(3)**:357-368.

Williams, J.R., Jones, C.A. and Dyke, P.T. (1990). The EPIC model documentation. . *USDA-ARS Technical Bulletin No*. 1768. U.S. Department of Agriculture, Washington, DC. pp. 3-9.

Willmott, C.J. 1981. On the validation of models. *Physical Geography,* **2**:184-194.

Willmott, C.J., and D.E. Wicks. 1980. An empirical method for the spatial interpolation of monthly precipitation within California. *Physical Geography,* **1**:59-73.

Wroblewitz, S., Hüther, L., Manderscheid, R., Weigel, H.J., Wätzig, H. and Dänicke, S. (2013). The effect of free air carbon dioxide enrichment and nitrogen fertilization on the chemical composition and nutritional value of wheat and barley grain. *Archives of Animal Nutrition,* 67**(4)**: 263-278.

Wu, D.X., Wang, G.X., Bai, Y.F. and Liao, J.X. (2004). Effects of elevated CO_2 concentration on growth, water use, yield and grain quality of wheat under two soil water levels. *Agriculture,Ecosystems & Environment,* 104**(3)**:493-507.

Xiao, G., Zhang, Q., Wang, R. and Xiong, Y. (2009). Effects of elevated CO_2 concentration, supplemental irrigation and nitrogenous fertilizer application on rain-fed spring wheat yield. *Acta Ecologica Sinica,* 29**(4)**:205-210.

Yang, L., Huang, J., Yang, H., Dong, G., Liu, G., Zhu, J., & Wang, Y. (2006). Seasonal changes in the effects of free-air CO_2 enrichment (FACE) on dry matter production and distribution of rice (Oryza sativa L.). *Field crops research,* 98 **(1)**: 12-19.

Yoshida, S., (1981) Fundamentals of rice crop science.: published by Int. Rice Res. Inst.

Zhang, X. C., Yu, X. F., & Ma, Y. F. (2013). Effect of nitrogen application and elevated CO_2 on photosynthetic gas exchange and electron transport in wheat leaves. *Photosynthetica,* 51 **(4)**:593-602.

Annexure-1

DSSAT 4.5 Generated Weather file for 2011-12 and 2012-13 [*.CLI file]

```
*CLIMATE:Roorkee

@ INSI      LAT     LONG  ELEV   TAV   AMP  SRAY  TMXY  TMNY  RAIY
  2011   29.800   78.600   260  23.8   8.6  17.6  29.6  18.1  1118
@START  DURN  ANGA  ANGB REFHT WNDHT SOURCE
  2011     2  0.25  0.50 -99.0 -99.0 Calculated_from_daily_data
@ GSST  GSDU
     1   365

*MONTHLY AVERAGES
@  MTH  SAMN  XAMN  NAMN  RTOT  RNUM  SHMN  AMTH  BMTH
     1  11.9  19.2   7.4  35.4   2.0   -99 0.250 0.500
     2  15.1  23.7  12.1  62.4   4.3   -99 0.250 0.500
     3  19.9  29.5  15.3   9.3   2.7   -99 0.250 0.500
     4  23.6  33.5  18.5  10.6   2.7   -99 0.250 0.500
     5  25.8  37.5  22.7  35.2   3.7   -99 0.250 0.500
     6  21.1  35.7  25.2 175.6  10.0   -99 0.250 0.500
     7  17.4  32.0  25.7 257.6  12.7   -99 0.250 0.500
     8  16.9  31.9  24.9 452.4  13.0   -99 0.250 0.500
     9  16.8  33.0  23.9  64.9   6.3   -99 0.250 0.500
    10  16.7  31.3  19.4   5.4   0.3   -99 0.250 0.500
    11  13.9  26.4  13.1   0.7   0.7   -99 0.250 0.500
    12  12.2  21.4   8.7   8.6   1.3   -99 0.250 0.500

*WGEN PARAMETERS
@  MTH  SDMN  SDSD  SWMN  SWSD  XDMN  XDSD  XWMN  XWSD  NAMN  NASD ALPHA  RTOT   PDW  RNUM
     1  12.0   0.8  10.6   0.2  19.3   4.0  18.2   1.8   7.4   2.5 0.353  35.4 0.037   2.0
     2  15.5   0.6  12.7   0.8  24.1   1.9  21.5   2.3  12.1   2.1 0.077  62.4 0.127   4.3
     3  20.1   0.6  17.6   0.8  29.6   2.7  27.9   5.8  15.3   2.5 0.599   9.3 0.089   2.7
     4  23.9   0.7  19.9   1.2  33.8   1.9  30.5   4.9  18.5   2.5 0.294  10.6 0.064   2.7
     5  25.8   0.6  25.3   0.7  37.7   2.0  36.5   3.0  22.7   2.2 0.272  35.2 0.093   3.7
     6  22.9   0.5  18.3   0.6  36.8   4.9  33.5   2.6  25.2   1.8 0.871 175.6 0.170  10.0
     7  18.6   0.4  16.0   0.4  32.5   2.0  31.4   2.2  25.7   1.0 0.472 257.6 0.308  12.7
     8  18.1   0.5  15.6   0.5  32.1   2.2  31.7   1.8  24.9   1.1 0.378 452.4 0.419  13.0
     9  17.2   0.6  15.4   0.5  33.2   1.6  32.4   1.4  23.9   1.6 0.162  64.9 0.190   6.3
    10  16.7   0.7  10.8   0.0  31.4   1.8  25.7   0.0  19.4   3.2 0.000   5.4 0.011   0.3
    11  13.9   0.7  13.3   0.0  26.4   1.8  25.6   0.0  13.1   1.7 0.000   0.7 0.023   0.7
    12  12.3   0.6   9.5   0.7  21.6   3.5  18.2   2.5   8.7   2.2 0.000   8.6 0.035   1.3

*RANGE CHECK VALUES
@       SRAD  TMAX  TMIN  RAIN  DEWP  WIND  SUNH   PAR  TDRY  TWET  EVAP  RHUM
MIN :    5.0 -10.0 -20.0   0.0   0.0   0.0   0.0   5.0   0.0   0.0   0.0   0.0
MAX :   85.0  40.0  30.0 600.0  25.0 500.0 100.0  85.0  35.0  25.0  15.0 100.0
RATE:   70.0  20.0  20.0 500.0   5.0 300.0  90.0  70.0  20.0  20.0  15.0  75.0

*FLAGGED DATA COUNT
@BEGYR BEGMN BEGDY ENDYR ENDMN ENDDY
     0     0     0     0     0     0
@          TOTAL   RAIN   TMAX   TMIN   SRAD   SUNH   DEWP   WIND    PAR   TDRY   TWET   EVAP   RHUM
Total  :       0      0      0      0      0      0      0      0      0      0      0      0      0
Valid  :       0      0      0      0      0      0      0      0      0      0      0      0      0
Missing:       0      0      0      0      0      0      0      0      0      0      0      0      0
Error  :       0      0      0      0      0      0      0      0      0      0      0      0      0
Above  :       0      0      0      0      0      0      0      0      0      0      0      0      0
Below  :       0      0      0      0      0      0      0      0      0      0      0      0      0
Rate   :       0      0      0      0      0      0      0      0      0      0      0      0      0
```

Table 1 : Summary of weather data used to generate DSSAT 4.5 weather file during 2011-13

Year	Month	Solar Radiation (MJ/m^2)	Max Temp (^0C)	Min Temp (^0C)	Rain (mm)
2011	Jan	12.1	20.1	8.6	0
	Feb	16.3	25.6	15.4	34.3
	Mar	21.7	30.0	15.3	11.4
	Apr	25.6	35.4	19.4	10.4
	May	27.5	38.5	23.8	103
	Jun	23.4	38.0	25.6	167.8
	Jul	21.2	33.7	26.1	479
	Aug	21.0	34.4	25.4	463.5
	Sep	19.1	35.4	25.0	47.8
	Oct	19.2	34.2	21.7	0
	Nov	13.7	28.5	17.1	0
	Dec	13.3	23.4	10.9	0
2012	Jan	12.3	21.4	8.4	12.3
	Feb	15.3	24.0	10.8	3.2
	Mar	19.1	30.3	16.4	12.9
	Apr	22.1	32.0	18.1	21
	May	25.2	37.4	22.2	1.5
	Jun	22.0	37.0	25.4	45.8
	Jul	14.9	30.8	25.4	125.7
	Aug	13.5	29.6	24.5	357.3
	Sep	15.2	31.5	23.6	118.3
	Oct	16.4	30.0	17.0	0
	Nov	13.9	25.4	11.4	0.5
	Dec	11.1	19.6	7.7	11.3
2013	Jan	11.2	16.2	5.3	94
	Feb	13.7	21.3	10.4	152
	Mar	19.0	28.0	14.3	3.5
	Apr	23.1	33.2	18.1	0.5
	May	24.6	36.7	22.1	1
	Jun	17.9	32.1	24.6	313.3
	Jul	16.0	31.6	25.6	168.1
	Aug	16.2	31.8	24.7	536.4
	Sep	16.2	32.0	23.0	28.7
	Oct	14.4	29.8	19.5	16.2
	Nov	14.2	25.3	10.8	1.5
	Dec	12.0	21.3	7.5	14.4

DSSAT 4.5 Generated Weather file for 2013-14 [*.CLI file]

```
*CLIMATE:Roorkee

@ INSI      LAT     LONG  ELEV   TAV   AMP  SRAY  TMXY  TMNY  RAIY
  2014   29.800   78.600   260  22.9   9.4  16.9  28.6  17.2  1101
@START  DURN  ANGA  ANGB REFHT WNDHT SOURCE
  2013     1  0.25  0.50 -99.0 -99.0 Calculated_from_daily_data
@ GSST  GSDU
     1   365

*MONTHLY AVERAGES
@  MTH  SAMN  XAMN  NAMN  RTOT  RNUM  SHMN  AMTH  BMTH
     1  10.8  16.6   6.5  96.4   3.5   -99 0.250 0.500
     2  13.7  20.9   9.9 104.8   5.0   -99 0.250 0.500
     3  18.5  27.1  14.1  20.4   4.5   -99 0.250 0.500
     4  23.2  32.7  17.5   7.4   3.5   -99 0.250 0.500
     5  24.3  37.5  23.2   4.0   2.0   -99 0.250 0.500
     6  21.2  35.1  24.4 165.1   6.5   -99 0.250 0.500
     7  17.0  33.0  25.9 219.6  12.5   -99 0.250 0.500
     8  17.1  32.7  24.8 348.8  10.5   -99 0.250 0.500
     9  16.5  32.2  22.9 108.7   8.0   -99 0.250 0.500
    10  14.9  29.6  18.7  11.6   1.5   -99 0.250 0.500
    11  14.4  25.7  10.8   0.8   0.5   -99 0.250 0.500
    12  11.8  20.6   7.1  13.4   2.5   -99 0.250 0.500

*WGEN PARAMETERS
@  MTH  SDMN  SDSD  SWMN  SWSD  XDMN  XDSD  XWMN  XWSD  NAMN  NASD ALPHA  RTOT   PDW  RNUM
     1  11.0   0.8   9.4   0.8  16.6   3.7  17.0   4.0   6.5   2.0 0.284  96.4 0.063   3.5
     2  14.3   0.5  10.7   0.7  21.5   2.0  18.0   3.5   9.9   2.1 0.288 104.8 0.143   5.0
     3  18.8   0.8  16.6   0.5  27.4   2.2  25.6   3.4  14.1   2.0 0.182  20.4 0.136   4.5
     4  23.7   0.7  19.3   0.4  33.3   2.2  28.1   1.7  17.5   2.0 0.268   7.4 0.104   3.5
     5  24.6   1.3  20.3   0.8  37.9   2.2  32.0   4.4  23.2   2.5 0.000   4.0 0.056   2.0
     6  22.1   0.4  16.9   0.5  36.4   3.9  30.6   3.4  24.4   1.3 0.800 165.1 0.125   6.5
     7  17.9   0.6  15.7   1.3  33.8   3.1  31.6   2.5  25.9   1.2 0.492 219.6 0.231  12.5
     8  17.6   0.6  16.0   0.5  33.5   1.7  31.1   1.8  24.8   0.9 0.390 348.8 0.276  10.5
     9  16.6   0.8  16.1   0.5  32.3   1.5  31.9   1.6  22.9   1.1 0.786 108.7 0.219   8.0
    10  15.0   0.9  13.5   0.8  29.7   1.5  27.5   5.2  18.7   3.2 0.000  11.6 0.054   1.5
    11  14.4   0.6  13.6   0.0  25.7   1.4  28.4   0.0  10.8   1.8 0.000   0.8 0.017   0.5
    12  12.1   0.0   8.7   0.0  20.9   3.6  17.1   1.6   7.1   1.8 0.000  13.4 0.054   2.5

*RANGE CHECK VALUES
@       SRAD  TMAX  TMIN  RAIN  DEWP  WIND  SUNH   PAR  TDRY  TWET  EVAP  RHUM
MIN :    5.0 -10.0 -20.0   0.0   0.0   0.0   0.0   5.0   0.0   0.0   0.0   0.0
MAX :   85.0  40.0  30.0 600.0  25.0 500.0 100.0  85.0  35.0  25.0  15.0 100.0
RATE:   70.0  20.0  20.0 500.0   5.0 300.0  90.0  70.0  20.0  20.0  15.0  75.0

*FLAGGED DATA COUNT
@BEGYR BEGMN BEGDY ENDYR ENDMN ENDDY
     0     0     0     0     0     0
@          TOTAL    RAIN    TMAX    TMIN    SRAD    SUNH    DEWP    WIND     PAR    TDRY    TWET    EVAP    RHUM
Total  :       0       0       0       0       0       0       0       0       0       0       0       0       0
Valid  :       0       0       0       0       0       0       0       0       0       0       0       0       0
Missing:       0       0       0       0       0       0       0       0       0       0       0       0       0
Error  :       0       0       0       0       0       0       0       0       0       0       0       0       0
Above  :       0       0       0       0       0       0       0       0       0       0       0       0       0
Below  :       0       0       0       0       0       0       0       0       0       0       0       0       0
Rate   :       0       0       0       0       0       0       0       0       0       0       0       0       0
```

Table 2: Summary of weather data used to generate DSSAT 4.5 weather file during 2013-14

Year	Month	Solar Radiation (MJ/m^2)	Max Temp (^{0}C)	Min Temp (^{0}C)	Rain (mm)
2013	Jan	11.2	16.2	5.3	94.0
	Feb	13.7	21.3	10.4	152.0
	Mar	19.0	28.0	14.3	3.5
	Apr	23.1	33.2	18.1	0.5
	May	24.6	36.7	22.1	1.0
	Jun	17.9	32.1	24.6	313.3
	Jul	16.0	31.6	25.6	168.1
	Aug	16.2	31.8	24.7	536.4
	Sep	16.2	32.0	23.0	28.7
	Oct	14.4	29.8	19.5	16.2
	Nov	14.2	25.3	10.8	1.5
	Dec	12.0	21.3	7.5	14.4
2014	Jan	10.4	17.1	7.7	98.8
	Feb	13.7	20.5	9.5	57.5
	Mar	18.0	26.2	13.8	37.2
	Apr	23.3	32.3	16.8	14.3
	May	24.1	38.4	24.3	7.0
	Jun	24.6	38.2	24.2	16.8
	Jul	18.1	34.3	26.2	271.1
	Aug	18.0	33.6	24.9	161.3
	Sep	16.7	32.4	22.9	188.8
	Oct	15.3	29.5	18.0	7.0
	Nov	14.6	26.1	10.8	0.0
	Dec	11.6	20.0	6.8	12.5

Annexure-2a

DSSAT 4.5 Simulation file 2011-12 (Validation of CO_2 experiment)

```
*SIMULATION OVERVIEW FILE


*DSSAT Cropping System Model Ver. 4.5.0.030          AUG 02, 2015; 15:56:21

*RUN   1        : T0
 MODEL          : CSCER045 - Wheat
 EXPERIMENT     : WHEA2011 WH SUNI2011WH EFFECT OF ELEVATED CO2 ON WHEAT CROP 20
 TREATMENT  1   : T0


 CROP           : Wheat               CULTIVAR : PBW 343   (org)  ECOTYPE :INWH01
 STARTING DATE  : NOV 25 1911
 PLANTING DATE  : NOV 25 1911    PLANTS/m2 : 33.0     ROW SPACING :  20.cm
 WEATHER        : WRDM   1911
 SOIL           : IITR791201     TEXTURE : CL    - Dhanauri
 SOIL INITIAL C : DEPTH:120cm EXTR. H2O:127.2mm  NO3: 46.2kg/ha  NH4:  5.3kg/ha
 WATER BALANCE  : IRRIGATE ON REPORTED DATE(S)
 IRRIGATION     :      450 mm IN     5 APPLICATIONS
 NITROGEN BAL.  : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER   :      120 kg/ha IN     3 APPLICATIONS
 RESIDUE/MANURE : INITIAL :   100 kg/ha ;    1500 kg/ha IN     1 APPLICATIONS
 ENVIRONM. OPT. : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= S  0.20
                  RAIN= A  0.00  CO2 = A  40.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT : WATER   :Y  NITROGEN:Y  N-FIX:N  PHOSPH :Y  PESTS   :N
                  PHOTO   :R  ET      :R  INFIL:S  HYDROL :R  SOM     :G
                  CO2     :D  NSWIT   :1  EVAP :R  SOIL   :2
 MANAGEMENT OPT : PLANTING:R  IRRIG   :R  FERT :R  RESIDUE:R  HARVEST:M
                  WEATHER :M  TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

   SOIL LOWER UPPER   SAT  EXTR  INIT   ROOT   BULK     pH    NO3    NH4    ORG
  DEPTH LIMIT LIMIT    SW    SW    SW   DIST   DENS                          C
   cm   cm3/cm3    cm3/cm3    cm3/cm3          g/cm3         ugN/g  ugN/g     %
--------------------------------------------------------------------------------
   0-  5 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
   5- 15 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  15- 30 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  30- 45 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
  45- 60 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
  60- 90 0.097 0.201 0.407 0.104 0.113   0.22   1.50   7.80   2.60   0.30   0.20
  90-120 0.082 0.195 0.419 0.113 0.099   0.12   1.42   7.80   2.60   0.30   0.00

TOT-120  12.1  24.8  49.4  12.7  14.0  <--cm   -  kg/ha-->  46.2    5.3  27000
SOIL ALBEDO    : 0.13      EVAPORATION LIMIT : 6.00        MIN. FACTOR  : 1.00
RUNOFF CURVE # :73.00      DRAINAGE RATE     : 0.40        FERT. FACTOR : 1.00

 Wheat      CULTIVAR :IN0013-PBW 343   (org)    ECOTYPE :INWH01
 P1V    :  20.000  P1D    : 70.0000  P5     :  800.00
 G1     :  20.000  G2     :  45.000  G3     :   1.500  PHINT  :  95.000


*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

 ...... DATE ......  GROWTH       BIOMASS   LEAF       CROP N      STRESS
 YEARDOY DOM MON DAP STAGE........ kg/ha AREA NUMBER  kg/ha   %    H2O    N
 1911329  25 Nov   0 7 Sowing         0  0.00   0.0     0   0.0  0.00  0.00
 1911331  27 Nov   2 8 Germinate      0  0.00   0.0     0   0.0  0.00  0.00
 1911340   6 Dec   8 9 Emergence      0  0.00   0.0     0   0.0  0.00  0.00
 1912055  24 Feb  91 1 Term Spklt  3678  1.32  13.7    53   1.7  0.05  0.00
 1912065   1 Mar  97 2 End Veg     5281  2.75  15.8    68   1.6  0.36  0.00
 1912069   9 Mar 105 3 End Ear Gr  6619  3.39  15.8    67   1.3  0.00  0.00
 1912076  19 Mar 115 4 Beg Gr Fil  8703  1.33  15.8    67   1.0  0.00  0.00
 1912109  12 Apr 139 5 End Gr Fil 12728  0.00  15.8    85   0.8  0.08  0.39
 1912109  12 Apr 139 6 Harvest    12728  0.00  15.8    85   0.8  0.00  0.00
```

BIOMASS = Above-ground dry weight (kg/ha)
LEAF AREA = Leaf area index (m2/m2)
LEAF NUMBER = Leaf number produced on main axis
CROP N = Above-ground N (kg/ha)
CROP N% = Above-ground N concentration (%)
H2O STRESS = Photosynthesis stress,average (0-1,0=none)
N STRESS = Photosynthesis stress,average (0-1,0=none)

*MAIN GROWTH AND DEVELOPMENT VARIABLES

@ VARIABLE	SIMULATED	MEASURED
Emergence (DAP)	08	-99
Anthesis (DAP)	98	-99
Maturity (DAP)	139	-99
Product wt (kg dm/ha;no loss)	5166	-99
Product unit weight (g dm)	0.040	-99.0
Product number (no/m2)	12914	-99
Product number (no/group)	36.8	-99.0
Product harvest index (ratio)	0.41	-99.00
Maximum leaf area index	3.4	-99.0
Final leaf number (one axis)	15.8	-99.0
Final shoot number (#/m2)	660	-99
Canopy (tops) wt (kg dm/ha)	12728	-99
Vegetative wt (kg dm/ha)	7562	0
Root wt (kg dm/ha)	540	-99
Assimilate wt (kg dm/ha)	12001	-99
Senesced wt (kg dm/ha)	780	-99
Reserves wt (kg dm/ha)	3231	-99
N uptake (kg/ha)	114.2	-99.0
N senesced (kg/ha)	22.7	-99.0
Above-ground N (kg/ha)	85.0	-99.0
Root N (kg/ha)	6.8	-99.0
Vegetative N (kg/ha)	8.8	-99.0
Product N (kg/ha)	76.1	-99.0
Product N harvest index (ratio)	0.90	-99.00
Product N (%)	1.6	-99.0
Vegetative N (%)	0.2	-99.0
Leaf+stem wt,anthesis (kg dm/ha)	5517	-99
Leaf+stem N,anthesis (kg/ha)	66.8	-99.0
Leaf N,anthesis (%)	4.3	-99.0

Seed N must be added to N uptake to obtain a balance with N in above-ground plus root material

Measured data are obtained from the A file,either directly or by calculation from other other variables using the expressions given below:

```
Product wt       Harvest wt (HWAH) / (Harvest%/100) (HPC)
Canopy wt        Grain wt (HWAM) + vegetative wt (VWAM)
Vegetative wt    Canopy wt (CWAM) - grain wt (HWAM)
  = leaf+stem+retained dead material
Product unit wt  Grain yield (HWAM)/grain number (G#AM)
Product #/area   Product#/tiller (H#SM) *
                                  tiller number (T#AM)
Product #/group  Product#/area (H#AM) /
                              tiller number (T#AM)
Harvest index    Product wt (HWAM)/Canopy wt.(CWAM)
```

The same procedure is followed for nitrogen aspects

*ENVIRONMENTAL AND STRESS FACTORS

Development Phase	Environment: Average: Time Span days	Temp Max øC	Temp Min øC	Solar Rad MJ/m2	Photop [day] hr	Cumulative: Rain mm	Evapo Trans mm	Stress (0=Min, 1=Max Stress): Water: Photo synth	Water: Growth	Nitrogen: Photo synth	Nitrogen: Growth	Phosphorus: Photo synth	Phosphorus: Growth
Germinate - Term Spklt	80	22.5	9.4	13.6	11.40	15.5	98.8	0.052	0.076	0.000	0.000	-99.00	-99.00
Term Spklt - End Veg	10	26.4	12.9	19.9	12.27	0.0	28.9	0.356	0.367	0.000	0.000	-99.00	-99.00

```
 End Veg    - End Ear Gr    4  30.8  16.8  21.1  12.48    0.4   18.6  0.000  0.000  0.000  0.000 -99.00 -99.00
 End Ear Gr - Beg Gr Fil    7  27.9  14.2  22.1  12.64   12.5   27.7  0.000  0.000  0.000  0.000 -99.00 -99.00
 Beg Gr Fil - End Gr Fil   33  31.6  17.5  23.7  13.26   17.3  107.8  0.078  0.102  0.394  0.394 -99.00 -99.00

 Germinate  - End Gr Fil  134  25.5  12.1  17.2  12.02   45.7  281.9  0.077  0.098  0.097  0.097 -99.00 -99.00
--------------------------------------------------------------------------------------------------------------

*WATER PRODUCTIVITY

 Growing season length: 139 days

 Precipitation during growth season         45.7 mm[rain]
   Dry Matter Productivity                 22.09 kg[DM]/m3[rain]          =  220.9 kg[DM]/ha per mm[rain]
   Yield Productivity                      10.72 kg[grain yield]/m3[rain] =  107.2 kg[yield]/ha per mm[rain]

 Evapotranspiration during growth season   281.9 mm[ET]
   Dry Matter Productivity                  3.58 kg[DM]/m3[ET]            =   35.8 kg[DM]/ha per mm[ET]
   Yield Productivity                       1.74 kg[grain yield]/m3[ET]   =   17.4 kg[yield]/ha per mm[ET]

 Transpiration during growth season        197.4 mm[EP]
   Dry Matter Productivity                  5.12 kg[DM]/m3[EP]            =   51.2 kg[DM]/ha per mm[EP]
   Yield Productivity                       2.48 kg[grain yield]/m3[EP]   =   24.8 kg[yield]/ha per mm[EP]

--------------------------------------------------------------------------------------------------------------

          WHEAT YIELD :     5166 kg/ha    [Dry weight]

**************************************************************************************************************

*DSSAT Cropping System Model Ver. 4.5.0.030            AUG 02, 2015; 15:56:21

*RUN   2        : T1
 MODEL          : CSCER045 - Wheat
 EXPERIMENT     : TEST2011 WH SUNI2011WH EFFECT OF ELEVATED CO2 ON WHEAT CROP 20
 TREATMENT  2   : T1

 CROP           : Wheat             CULTIVAR : PBW 343   (org)  ECOTYPE :INWH01
 STARTING DATE  : NOV 25 1911
 PLANTING DATE  : NOV 25 1911    PLANTS/m2 : 33.0     ROW SPACING :  20.cm
 WEATHER        : WRDM   1911
 SOIL           : IITR791201     TEXTURE : CL    - Dhanauri
 SOIL INITIAL C : DEPTH:120cm EXTR. H2O:127.2mm  NO3: 46.2kg/ha  NH4:  5.3kg/ha
 WATER BALANCE  : IRRIGATE ON REPORTED DATE(S)
 IRRIGATION     :      450 mm IN      5 APPLICATIONS
 NITROGEN BAL.  : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER   :      120 kg/ha IN     3 APPLICATIONS
 RESIDUE/MANURE : INITIAL :   100 kg/ha ;    1500 kg/ha IN     1 APPLICATIONS
 ENVIRONM. OPT. : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= S  0.00
                  RAIN= A  0.00  CO2 = A  80.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT : WATER   :Y  NITROGEN:Y  N-FIX:N  PHOSPH :Y  PESTS  :N
                  PHOTO   :R  ET      :R  INFIL:S  HYDROL :R  SOM    :G
                  CO2     :D  NSWIT   :1  EVAP :R  SOIL   :2
 MANAGEMENT OPT : PLANTING:R  IRRIG   :R  FERT :R  RESIDUE:R  HARVEST:M
                  WEATHER :M  TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

   SOIL LOWER UPPER   SAT  EXTR  INIT   ROOT   BULK     pH    NO3    NH4    ORG
  DEPTH LIMIT LIMIT    SW    SW    SW   DIST   DENS                         C
   cm   cm3/cm3    cm3/cm3   cm3/cm3         g/cm3         ugN/g  ugN/g     %
--------------------------------------------------------------------------------
   0-  5 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
   5- 15 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  15- 30 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  30- 45 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
  45- 60 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
  60- 90 0.097 0.201 0.407 0.104 0.113   0.22   1.50   7.80   2.60   0.30   0.20
  90-120 0.082 0.195 0.419 0.113 0.099   0.12   1.42   7.80   2.60   0.30   0.00

TOT-120  12.1  24.8  49.4  12.7  14.0  <--cm   -  kg/ha-->  46.2    5.3  27000
SOIL ALBEDO    : 0.13      EVAPORATION LIMIT : 6.00         MIN. FACTOR  : 1.00
RUNOFF CURVE # :73.00      DRAINAGE RATE     : 0.40         FERT. FACTOR : 1.00

 Wheat      CULTIVAR :IN0013-PBW 343   (org)    ECOTYPE :INWH01
 P1V    :  20.000  P1D    : 70.0000  P5     :  800.00
```

G1 : 20.000 G2 : 45.000 G3 : 1.500 PHINT : 95.000

*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

...... DATE				GROWTH	BIOMASS	LEAF		CROP N		STRESS	
YEARDOY	DOM	MON	DAP	STAGE........	kg/ha	AREA	NUMBER	kg/ha	%	H2O	N
1911329	25	Nov	0	7 Sowing	0	0.00	0.0	0	0.0	0.00	0.00
1911331	27	Nov	2	8 Germinate	0	0.00	0.0	0	0.0	0.00	0.00
1911340	6	Dec	11	9 Emergence	0	0.00	0.0	0	0.0	0.00	0.00
1912055	24	Feb	91	1 Term Spklt	4039	1.35	13.7	55	1.6	0.05	0.00
1912065	1	Mar	97	2 End Veg	5853	2.79	15.8	70	1.6	0.35	0.00
1912069	8	Mar	104	3 End Ear Gr	7380	3.32	15.8	69	1.3	0.00	0.00
1912076	11	Mar	112	4 Beg Gr Fil	9685	1.46	15.8	69	1.0	0.00	0.00
1912108	12	Apr	139	5 End Gr Fil	13754	0.00	15.8	88	0.8	0.07	0.43
1912108	12	Apr	139	6 Harvest	13754	0.00	15.8	88	0.8	0.00	0.00

*MAIN GROWTH AND DEVELOPMENT VARIABLES

@ VARIABLE	SIMULATED	MEASURED
--------	---------	--------
Emergence (DAP)	08	-99
Anthesis (DAP)	095	-99
Maturity (DAP)	139	-99
Product wt (kg dm/ha;no loss)	5361	-99
Product unit weight (g dm)	0.040	-99.0
Product number (no/m2)	13402	-99
Product number (no/group)	41.2	-99.0
Product harvest index (ratio)	0.39	-99.00
Maximum leaf area index	3.3	-99.0
Final leaf number (one axis)	15.8	-99.0
Final shoot number (#/m2)	660	-99
Canopy (tops) wt (kg dm/ha)	13754	-99
Vegetative wt (kg dm/ha)	8393	0
Root wt (kg dm/ha)	568	-99
Assimilate wt (kg dm/ha)	12318	-99
Senesced wt (kg dm/ha)	804	-99
Reserves wt (kg dm/ha)	3125	-99
N uptake (kg/ha)	118.0	-99.0
N senesced (kg/ha)	23.3	-99.0
Above-ground N (kg/ha)	87.7	-99.0
Root N (kg/ha)	7.2	-99.0
Vegetative N (kg/ha)	9.1	-99.0
Product N (kg/ha)	78.6	-99.0
Product N harvest index (ratio)	0.90	-99.00
Product N (%)	1.5	-99.0
Vegetative N (%)	0.2	-99.0
Leaf+stem wt,anthesis (kg dm/ha)	5826	-99
Leaf+stem N,anthesis (kg/ha)	68.5	-99.0
Leaf N,anthesis (%)	4.3	-99.0

*ENVIRONMENTAL AND STRESS FACTORS

Development Phase	Environment: Average					Environment: Cumulative		Stress (0=Min, 1=Max Stress): Water		Nitrogen		Phosphorus	
	Time Span days	Temp Max øC	Temp Min øC	Solar Rad MJ/m2	Photop [day] hr	Rain mm	Evapo Trans mm	Photo synth	Growth	Photo synth	Growth	Photo synth	Growth
Germinate - Term Spklt	80	22.5	9.6	13.6	11.40	15.5	98.7	0.045	0.070	0.000	0.000	-99.00	-99.00
Term Spklt - End Veg	10	26.4	13.1	19.9	12.27	0.0	28.8	0.351	0.363	0.000	0.000	-99.00	-99.00
End Veg - End Ear Gr	4	30.8	17.0	21.1	12.48	0.4	18.6	0.000	0.000	0.000	0.000	-99.00	-99.00
End Ear Gr - Beg Gr Fil	7	27.9	14.4	22.1	12.64	12.5	27.6	0.000	0.000	0.000	0.000	-99.00	-99.00
Beg Gr Fil - End Gr Fil	32	31.6	17.6	23.6	13.24	17.3	105.2	0.073	0.096	0.426	0.426	-99.00	-99.00
Germinate - End Gr Fil	134	25.5	12.3	17.1	12.00	45.7	281.8	0.071	0.092	0.102	0.102	-99.00	-99.00

*WATER PRODUCTIVITY

Growing season length: 139 days

Precipitation during growth season 45.7 mm[rain]

```
  Dry Matter Productivity              22.61 kg[DM]/m3[rain]          =  226.1 kg[DM]/ha per mm[rain]
  Yield Productivity                   11.33 kg[grain yield]/m3[rain] =  113.3 kg[yield]/ha per mm[rain]

 Evapotranspiration during growth season   281.8 mm[ET]
  Dry Matter Productivity               3.67 kg[DM]/m3[ET]            =   36.7 kg[DM]/ha per mm[ET]
  Yield Productivity                    1.84 kg[grain yield]/m3[ET]   =   18.4 kg[yield]/ha per mm[ET]

 Transpiration during growth season        197.0 mm[EP]
  Dry Matter Productivity               5.25 kg[DM]/m3[EP]            =   52.5 kg[DM]/ha per mm[EP]
  Yield Productivity                    2.63 kg[grain yield]/m3[EP]   =   26.3 kg[yield]/ha per mm[EP]

------------------------------------------------------------------------------------------------------------

        WHEAT YIELD :     5361 kg/ha    [Dry weight]

************************************************************************************************************


*DSSAT Cropping System Model Ver. 4.5.0.030           AUG 02, 2015; 15:56:22

*RUN   3        : T2
 MODEL          : CSCER045 - Wheat
 EXPERIMENT     : TEST2011 WH SUNI2011WH EFFECT OF ELEVATED CO2 ON WHEAT CROP 20
 TREATMENT  3   : T2


 CROP           : Wheat           CULTIVAR : PBW 343   (org)  ECOTYPE :INWH01
 STARTING DATE  : NOV 25 1911
 PLANTING DATE  : NOV 25 1911    PLANTS/m2 : 33.0     ROW SPACING :  20.cm
 WEATHER        : WRDM   1911
 SOIL           : IITR791201     TEXTURE : CL    - Dhanauri
 SOIL INITIAL C : DEPTH:120cm EXTR. H2O:127.2mm  NO3: 46.2kg/ha  NH4:  5.3kg/ha
 WATER BALANCE  : IRRIGATE ON REPORTED DATE(S)
 IRRIGATION     :      450 mm IN     5 APPLICATIONS
 NITROGEN BAL.  : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER   :      120 kg/ha IN     3 APPLICATIONS
 RESIDUE/MANURE : INITIAL :   100 kg/ha ;    1500 kg/ha IN     1 APPLICATIONS
 ENVIRONM. OPT. : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= A  0.50
                  RAIN= A  0.00  CO2 = A 200.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT : WATER   :Y  NITROGEN:Y  N-FIX:N  PHOSPH :Y  PESTS  :N
                  PHOTO   :R  ET      :R  INFIL:S  HYDROL :R  SOM    :G
                  CO2     :D  NSWIT   :1  EVAP :R  SOIL   :2
 MANAGEMENT OPT : PLANTING:R  IRRIG   :R  FERT :R  RESIDUE:R  HARVEST:M
                  WEATHER :M  TILLAGE :N
```

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

SOIL DEPTH cm	LOWER LIMIT cm3/cm3	UPPER LIMIT	SAT SW cm3/cm3	EXTR SW	INIT SW cm3/cm3	ROOT DIST	BULK DENS g/cm3	pH	NO3 ugN/g	NH4 ugN/g	ORG C %
0- 5	0.121	0.224	0.414	0.103	0.136	1.00	1.50	7.80	2.60	0.30	0.20
5- 15	0.121	0.224	0.414	0.103	0.136	1.00	1.50	7.80	2.60	0.30	0.20
15- 30	0.121	0.224	0.414	0.103	0.136	1.00	1.50	7.80	2.60	0.30	0.20
30- 45	0.104	0.208	0.406	0.104	0.120	0.41	1.50	7.80	2.60	0.30	0.20
45- 60	0.104	0.208	0.406	0.104	0.120	0.41	1.50	7.80	2.60	0.30	0.20
60- 90	0.097	0.201	0.407	0.104	0.113	0.22	1.50	7.80	2.60	0.30	0.20
90-120	0.082	0.195	0.419	0.113	0.099	0.12	1.42	7.80	2.60	0.30	0.00

```
TOT-120  12.1  24.8  49.4  12.7  14.0  <--cm   -  kg/ha-->   46.2    5.3  27000
SOIL ALBEDO    : 0.13       EVAPORATION LIMIT : 6.00        MIN. FACTOR  : 1.00
RUNOFF CURVE # :73.00       DRAINAGE RATE     : 0.40        FERT. FACTOR : 1.00

 Wheat      CULTIVAR :IN0013-PBW 343   (org)    ECOTYPE :INWH01
 P1V    :  20.000  P1D    : 70.0000  P5     :  800.00
 G1     :  20.000  G2     :  45.000  G3     :   1.500  PHINT  :  95.000
```

*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

YEARDOY	DOM	MON	DAP	GROWTH STAGE	BIOMASS kg/ha	LEAF AREA	LEAF NUMBER	CROP N kg/ha	CROP N %	STRESS H2O	STRESS N
1911329	25	Nov	0	7 Sowing	0	0.00	0.0	0	0.0	0.00	0.00
1911331	27	Nov	2	8 Germinate	0	0.00	0.0	0	0.0	0.00	0.00

1911340	6	Dec	11	9	Emergence	0	0.00	0.0	0	0.0	0.00	0.00
1912055	24	Feb	91	1	Term Spklt	4765	1.53	13.9	60	1.5	0.03	0.00
1912065	27	Feb	95	2	End Veg	6818	2.97	16.0	75	1.4	0.34	0.00
1912069	7	Mar	103	3	End Ear Gr	8508	3.48	16.0	74	1.2	0.00	0.00
1912076	13	Mar	109	4	Beg Gr Fil	11093	1.50	16.0	74	0.9	0.00	0.00
1912108	05	Apr	132	5	End Gr Fil	15509	0.00	16.0	97	0.8	0.07	0.45
1912108	05	Apr	132	6	Harvest	15509	0.00	16.0	97	0.8	0.00	0.00

*MAIN GROWTH AND DEVELOPMENT VARIABLES

@ VARIABLE	SIMULATED	MEASURED
Emergence (DAP)	07	-99
Anthesis (DAP)	97	-99
Maturity (DAP)	132	-99
Product wt (kg dm/ha;no loss)	6008	-99
Product unit weight (g dm)	0.043	-99.0
Product number (no/m2)	13973	-99
Product number (no/group)	49.7	-99.0
Product harvest index (ratio)	0.39	-99.00
Maximum leaf area index	3.5	-99.0
Final leaf number (one axis)	16.0	-99.0
Final shoot number (#/m2)	660	-99
Canopy (tops) wt (kg dm/ha)	15509	-99
Vegetative wt (kg dm/ha)	9501	0
Root wt (kg dm/ha)	657	-99
Assimilate wt (kg dm/ha)	14064	-99
Senesced wt (kg dm/ha)	870	-99
Reserves wt (kg dm/ha)	3464	-99
N uptake (kg/ha)	129.8	-99.0
N senesced (kg/ha)	24.5	-99.0
Above-ground N (kg/ha)	97.2	-99.0
Root N (kg/ha)	8.3	-99.0
Vegetative N (kg/ha)	10.0	-99.0
Product N (kg/ha)	87.2	-99.0
Product N harvest index (ratio)	0.90	-99.00
Product N (%)	1.5	-99.0
Vegetative N (%)	0.2	-99.0
Leaf+stem wt,anthesis (kg dm/ha)	6582	-99
Leaf+stem N,anthesis (kg/ha)	73.9	-99.0
Leaf N,anthesis (%)	4.4	-99.0

*ENVIRONMENTAL AND STRESS FACTORS

Development Phase	Environment							Stress (0=Min, 1=Max Stress)					
		Average				Cumulative		Water		Nitrogen		Phosphorus	
	Time Span days	Temp Max øC	Temp Min øC	Solar Rad MJ/m2	Photop [day] hr	Rain mm	Evapo Trans mm	Photo synth	Growth	Photo synth	Growth	Photo synth	Growth
Germinate - Term Spklt	80	22.5	10.0	13.6	11.40	15.5	98.7	0.028	0.052	0.000	0.000	-99.00	-99.00
Term Spklt - End Veg	10	26.4	13.6	19.9	12.27	0.0	28.5	0.340	0.355	0.001	0.001	-99.00	-99.00
End Veg - End Ear Gr	4	30.8	17.5	21.1	12.48	0.4	18.2	0.000	0.000	0.000	0.000	-99.00	-99.00
End Ear Gr - Beg Gr Fil	7	27.9	14.9	22.1	12.64	12.5	28.3	0.000	0.000	0.000	0.000	-99.00	-99.00
Beg Gr Fil - End Gr Fil	32	31.6	18.1	23.6	13.24	17.3	105.7	0.073	0.094	0.449	0.449	-99.00	-99.00
Germinate - End Gr Fil	134	25.5	12.7	17.1	12.00	45.7	282.2	0.060	0.080	0.107	0.107	-99.00	-99.00

*WATER PRODUCTIVITY

Growing season length: 132 days

```
Precipitation during growth season         45.7 mm[rain]
  Dry Matter Productivity                 25.89 kg[DM]/m3[rain]          =  258.9 kg[DM]/ha per mm[rain]
  Yield Productivity                      13.36 kg[grain yield]/m3[rain] =  133.6 kg[yield]/ha per mm[rain]

Evapotranspiration during growth season   282.2 mm[ET]
  Dry Matter Productivity                  4.19 kg[DM]/m3[ET]            =   41.9 kg[DM]/ha per mm[ET]
  Yield Productivity                       2.16 kg[grain yield]/m3[ET]   =   21.6 kg[yield]/ha per mm[ET]

Transpiration during growth season        197.7 mm[EP]
  Dry Matter Productivity                  5.99 kg[DM]/m3[EP]            =   59.9 kg[DM]/ha per mm[EP]
  Yield Productivity                       3.09 kg[grain yield]/m3[EP]   =   30.9 kg[yield]/ha per mm[EP]
```

```
------------------------------------------------------------------------------------------------------------------

         WHEAT YIELD :     6008 kg/ha    [Dry weight]

******************************************************************************************************************

*DSSAT Cropping System Model Ver. 4.5.0.030             AUG 02, 2015; 15:56:22

*RUN   4         : T3
 MODEL           : CSCER045 - Wheat
 EXPERIMENT      : TEST2011 WH SUNI2011WH EFFECT OF ELEVATED CO2 ON WHEAT CROP 20
 TREATMENT  4    : T3


 CROP            : Wheat            CULTIVAR : PBW 343    (org)  ECOTYPE :INWH01
 STARTING DATE   : NOV 25 1911
 PLANTING DATE   : NOV 25 1911    PLANTS/m2 : 33.0     ROW SPACING :  20.cm
 WEATHER         : WRDM   1911
 SOIL            : IITR791201     TEXTURE : CL    - Dhanauri
 SOIL INITIAL C  : DEPTH:120cm EXTR. H2O:127.2mm  NO3: 46.2kg/ha  NH4:  5.3kg/ha
 WATER BALANCE   : IRRIGATE ON REPORTED DATE(S)
 IRRIGATION      :      450 mm IN     5 APPLICATIONS
 NITROGEN BAL.   : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER    :      120 kg/ha IN     3 APPLICATIONS
 RESIDUE/MANURE  : INITIAL :   100 kg/ha ;    1500 kg/ha IN     1 APPLICATIONS
 ENVIRONM. OPT.  : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= A  0.00
                   RAIN= A  0.00  CO2 = A 250.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT  : WATER   :Y  NITROGEN:Y  N-FIX:N  PHOSPH :Y  PESTS  :N
                   PHOTO   :R  ET      :R  INFIL:S  HYDROL :R  SOM    :G
                   CO2     :D  NSWIT   :1  EVAP :R  SOIL   :2
 MANAGEMENT OPT  : PLANTING:R  IRRIG   :R  FERT :R  RESIDUE:R  HARVEST:M
                   WEATHER :M  TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

   SOIL LOWER UPPER   SAT  EXTR  INIT   ROOT   BULK     pH    NO3    NH4    ORG
  DEPTH LIMIT LIMIT    SW    SW    SW   DIST   DENS                          C
   cm   cm3/cm3    cm3/cm3    cm3/cm3          g/cm3         ugN/g  ugN/g    %
--------------------------------------------------------------------------------
  0-  5 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  5- 15 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
 15- 30 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
 30- 45 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
 45- 60 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
 60- 90 0.097 0.201 0.407 0.104 0.113   0.22   1.50   7.80   2.60   0.30   0.20
 90-120 0.082 0.195 0.419 0.113 0.099   0.12   1.42   7.80   2.60   0.30   0.00

TOT-120  12.1  24.8  49.4  12.7  14.0  <--cm   -  kg/ha-->   46.2    5.3  27000
SOIL ALBEDO    : 0.13      EVAPORATION LIMIT : 6.00         MIN. FACTOR  : 1.00
RUNOFF CURVE # :73.00      DRAINAGE RATE     : 0.40         FERT. FACTOR : 1.00

 Wheat      CULTIVAR :IN0013-PBW 343   (org)    ECOTYPE :INWH01
 P1V    :  20.000  P1D    : 70.0000  P5     :  800.00
 G1     :  20.000  G2     :  45.000  G3     :   1.500  PHINT  :  95.000


*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

 ...... DATE ......  GROWTH       BIOMASS   LEAF       CROP N      STRESS
 YEARDOY DOM MON DAP STAGE........ kg/ha AREA NUMBER  kg/ha   %   H2O    N
 1911329  25 Nov   0 7 Sowing          0  0.00   0.0      0   0.0  0.00  0.00
 1911331  27 Nov   2 8 Germinate       0  0.00   0.0      0   0.0  0.00  0.00
 1911340   6 Dec  11 9 Emergence       0  0.00   0.0      0   0.0  0.00  0.00
 1912055  20 Feb  88 1 Term Spklt  5370  1.65  13.7     61   1.4  0.01  0.00
 1912065  24 Feb  92 2 End Veg     7875  3.49  15.8     77   1.3  0.32  0.00
 1912069   3 Mar  99 3 End Ear Gr  9940  3.59  15.8     77   1.1  0.00  0.00
 1912076  09 Mar 105 4 Beg Gr Fil 12951  1.60  15.8     77   0.9  0.00  0.00
 1912108  06 Apr 133 5 End Gr Fil 17635  0.00  15.8     99   0.8  0.08  0.48
 1912108  06 Apr 133 6 Harvest    17635  0.00  15.8     99   0.8  0.00  0.00

*MAIN GROWTH AND DEVELOPMENT VARIABLES

@     VARIABLE                          SIMULATED     MEASURED
```

Emergence (DAP)	09	-99
Anthesis (DAP)	094	-99
Maturity (DAP)	133	-99
Product wt (kg dm/ha;no loss)	6791	-99
Product unit weight (g dm)	0.041	-99.0
Product number (no/m2)	16564	-99
Product number (no/group)	47.2	-99.0
Product harvest index (ratio)	0.39	-99.00
Maximum leaf area index	3.6	-99.0
Final leaf number (one axis)	15.8	-99.0
Final shoot number (#/m2)	660	-99
Canopy (tops) wt (kg dm/ha)	17635	-99
Vegetative wt (kg dm/ha)	10844	0
Root wt (kg dm/ha)	700	-99
Assimilate wt (kg dm/ha)	14671	-99
Senesced wt (kg dm/ha)	869	-99
Reserves wt (kg dm/ha)	3441	-99
N uptake (kg/ha)	131.7	-99.0
N senesced (kg/ha)	23.8	-99.0
Above-ground N (kg/ha)	99.3	-99.0
Root N (kg/ha)	8.8	-99.0
Vegetative N (kg/ha)	10.5	-99.0
Product N (kg/ha)	88.8	-99.0
Product N harvest index (ratio)	0.89	-99.00
Product N (%)	1.4	-99.0
Vegetative N (%)	0.2	-99.0
Leaf+stem wt,anthesis (kg dm/ha)	7368	-99
Leaf+stem N,anthesis (kg/ha)	76.8	-99.0
Leaf N,anthesis (%)	4.3	-99.0

*ENVIRONMENTAL AND STRESS FACTORS

Development Phase	Environment: Average					Environment: Cumulative		Stress (0=Min, 1=Max Stress): Water		Nitrogen		Phosphorus	
	Time Span days	Temp Max øC	Temp Min øC	Solar Rad MJ/m2	Photop [day] hr	Rain mm	Evapo Trans mm	Photo synth	Growth	Photo synth	Growth	Photo synth	Growth
Germinate - Term Spklt	80	22.5	9.6	13.6	11.40	15.5	97.9	0.012	0.035	0.000	0.000	-99.00	-99.00
Term Spklt - End Veg	10	26.4	13.1	19.9	12.27	0.0	28.5	0.320	0.340	0.002	0.002	-99.00	-99.00
End Veg - End Ear Gr	4	30.8	17.0	21.1	12.48	0.4	18.2	0.000	0.000	0.003	0.003	-99.00	-99.00
End Ear Gr - Beg Gr Fil	7	27.9	14.4	22.1	12.64	12.5	28.6	0.000	0.000	0.000	0.000	-99.00	-99.00
Beg Gr Fil - End Gr Fil	32	31.6	17.6	23.6	13.24	17.3	106.4	0.081	0.102	0.483	0.483	-99.00	-99.00
Germinate - End Gr Fil	134	25.5	12.3	17.1	12.00	45.7	282.5	0.050	0.070	0.116	0.116	-99.00	-99.00

*WATER PRODUCTIVITY

Growing season length: 133 days

Precipitation during growth season 45.7 mm[rain]
Dry Matter Productivity 27.03 kg[DM]/m3[rain] = 270.3 kg[DM]/ha per mm[rain]
Yield Productivity 14.34 kg[grain yield]/m3[rain] = 143.4 kg[yield]/ha per mm[rain]

Evapotranspiration during growth season 282.5 mm[ET]
Dry Matter Productivity 4.37 kg[DM]/m3[ET] = 43.7 kg[DM]/ha per mm[ET]
Yield Productivity 2.32 kg[grain yield]/m3[ET] = 23.2 kg[yield]/ha per mm[ET]

Transpiration during growth season 199.1 mm[EP]
Dry Matter Productivity 6.20 kg[DM]/m3[EP] = 62.0 kg[DM]/ha per mm[EP]
Yield Productivity 3.29 kg[grain yield]/m3[EP] = 32.9 kg[yield]/ha per mm[EP]

WHEAT YIELD : 6791 kg/ha [Dry weight]

Annexure-2b

DSSAT 4.5 Simulation file 2012-13 (Validation of CO_2 experiment)

```
*SIMULATION OVERVIEW FILE


*DSSAT Cropping System Model Ver. 4.5.0.030          AUG 01, 2015; 13:01:54

*RUN   1        : T0
 MODEL          : CSCER045 - Wheat
 EXPERIMENT     : TEST2012 WH TEST2011WH SUNI2011WH EFFECT OF ELEVATED CO2 ON WH
 TREATMENT  1   : T0


 CROP           : Wheat             CULTIVAR : PBW 343   (org)  ECOTYPE :INWH01
 STARTING DATE  : NOV 25 1911
 PLANTING DATE  : NOV 20 1912     PLANTS/m2 : 33.0     ROW SPACING :  20.cm
 WEATHER        : WRDM   1911
 SOIL           : IITR791201      TEXTURE : CL    - Dhanauri
 SOIL INITIAL C : DEPTH:120cm EXTR. H2O:127.2mm  NO3: 46.2kg/ha  NH4:  5.3kg/ha
 WATER BALANCE  : IRRIGATE ON REPORTED DATE(S)
 IRRIGATION     :      210 mm IN     3 APPLICATIONS
 NITROGEN BAL.  : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER   :      120 kg/ha IN     3 APPLICATIONS
 RESIDUE/MANURE : INITIAL :   100 kg/ha ;        0 kg/ha IN     0 APPLICATIONS
 ENVIRONM. OPT. : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= A  0.00
                  RAIN= A  0.00  CO2 = A   0.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT : WATER   :Y  NITROGEN:Y  N-FIX:N  PHOSPH :N  PESTS  :N
                  PHOTO   :C  ET      :R  INFIL:S  HYDROL :R  SOM    :G
                  CO2     :D  NSWIT   :1  EVAP :R  SOIL   :2
 MANAGEMENT OPT : PLANTING:R  IRRIG   :R  FERT :R  RESIDUE:N  HARVEST:M
                  WEATHER :M  TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

   SOIL LOWER UPPER   SAT  EXTR  INIT   ROOT   BULK     pH    NO3    NH4    ORG
  DEPTH LIMIT LIMIT    SW    SW    SW   DIST   DENS                          C
   cm   cm3/cm3    cm3/cm3    cm3/cm3          g/cm3         ugN/g  ugN/g     %
-------------------------------------------------------------------------------
   0-  5 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
   5- 15 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  15- 30 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  30- 45 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
  45- 60 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
  60- 90 0.097 0.201 0.407 0.104 0.113   0.22   1.50   7.80   2.60   0.30   0.20
  90-120 0.082 0.195 0.419 0.113 0.099   0.12   1.42   7.80   2.60   0.30   0.00

TOT-120  12.1  24.8  49.4  12.7  14.0  <--cm   -  kg/ha-->  46.2    5.3  27000
SOIL ALBEDO    : 0.13       EVAPORATION LIMIT : 6.00        MIN. FACTOR  : 1.00
RUNOFF CURVE # :73.00       DRAINAGE RATE     : 0.40        FERT. FACTOR : 1.00

 Wheat      CULTIVAR :IN0013-PBW 343   (org)    ECOTYPE :INWH01
 P1V    :  20.000  P1D    : 70.0000  P5     :  800.00
 G1     :  20.000  G2     :  45.000  G3     :   1.500  PHINT  :  95.000


*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

 ...... DATE ......  GROWTH        BIOMASS   LEAF       CROP N       STRESS
 YEARDOY DOM MON DAP STAGE........ kg/ha AREA NUMBER  kg/ha   %    H2O    N
 1912325  20 Nov   0 7 Sowing         0  0.00   0.0     0   0.0  0.00  0.00
 1912326  21 Nov   1 8 Germinate      0  0.00   0.0     0   0.0  0.00  0.00
 1912329  24 Nov   7 9 Emergence      0  0.00   0.0     0   0.0  0.00  0.00
 1913045  14 Feb  86 1 Term Spklt  2521  1.42  11.5    48   2.0  0.00  0.00
 1913056  25 Feb  97 2 End Veg     3713  3.03  13.3    69   1.9  0.00  0.01
 1913062   3 Mar 103 3 End Ear Gr  4742  3.41  13.3    70   1.5  0.00  0.04
 1913069  10 Mar 110 4 Beg Gr Fil  6235  1.61  13.3    69   1.1  0.00  0.00
 1913104  09 Apr 141 5 End Gr Fil 10592  0.00  13.3    86   0.8  0.02  0.33
 1913104  09 Apr 141 6 Harvest    10592  0.00  13.3    86   0.8  0.00  0.00
```

BIOMASS = Above-ground dry weight (kg/ha)
LEAF AREA = Leaf area index (m2/m2)
LEAF NUMBER = Leaf number produced on main axis
CROP N = Above-ground N (kg/ha)
CROP N% = Above-ground N concentration (%)
H2O STRESS = Photosynthesis stress,average (0-1,0=none)
N STRESS = Photosynthesis stress,average (0-1,0=none)

*MAIN GROWTH AND DEVELOPMENT VARIABLES

@ VARIABLE	SIMULATED	MEASURED
Emergence (DAP)	7	-99
Anthesis (DAP)	102	-99
Maturity (DAP)	141	-99
Product wt (kg dm/ha;no loss)	4666	-99
Product unit weight (g dm)	0.039	-99.0
Product number (no/m2)	11963	-99
Product number (no/group)	36.0	-99.0
Product harvest index (ratio)	0.44	-99.00
Maximum leaf area index	3.4	-99.0
Final leaf number (one axis)	13.3	-99.0
Final shoot number (#/m2)	659	-99
Canopy (tops) wt (kg dm/ha)	10592	-99
Vegetative wt (kg dm/ha)	5926	0
Root wt (kg dm/ha)	460	-99
Assimilate wt (kg dm/ha)	11800	-99
Senesced wt (kg dm/ha)	481	-99
Reserves wt (kg dm/ha)	3904	-99
N uptake (kg/ha)	103.5	-99.0
N senesced (kg/ha)	11.6	-99.0
Above-ground N (kg/ha)	86.3	-99.0
Root N (kg/ha)	5.8	-99.0
Vegetative N (kg/ha)	9.8	-99.0
Product N (kg/ha)	76.5	-99.0
Product N harvest index (ratio)	0.89	-99.00
Product N (%)	1.7	-99.0
Vegetative N (%)	0.2	-99.0
Leaf+stem wt,anthesis (kg dm/ha)	5022	-99
Leaf+stem N,anthesis (kg/ha)	69.4	-99.0
Leaf N,anthesis (%)	4.3	-99.0

Seed N must be added to N uptake to obtain a
balance with N in above-ground plus root material

Measured data are obtained from the A file,either
directly or by calculation from other other variables
using the expressions given below:

```
Product wt        Harvest wt (HWAH) / (Harvest%/100) (HPC)
Canopy wt         Grain wt (HWAM) + vegetative wt (VWAM)
Vegetative wt     Canopy wt (CWAM) - grain wt (HWAM)
  = leaf+stem+retained dead material
Product unit wt   Grain yield (HWAM)/grain number (G#AM)
Product #/area    Product#/tiller (H#SM) *
                                tiller number (T#AM)
Product #/group   Product#/area (H#AM) /
                          tiller number (T#AM)
Harvest index     Product wt (HWAM)/Canopy wt.(CWAM)
```

The same procedure is followed for nitrogen aspects

*ENVIRONMENTAL AND STRESS FACTORS

Development Phase	Environment: Average					Environment: Cumulative		Stress (0=Min, 1=Max Stress): Water		Nitrogen		Phosphorus	
	Time Span days	Temp Max øC	Temp Min øC	Solar Rad MJ/m2	Photop [day] hr	Rain mm	Evapo Trans mm	Photo synth	Growth	Photo synth	Growth	Photo synth	Growth
Germinate - Term Spklt	82	18.9	7.2	12.5	11.31	177.3	98.2	0.000	0.000	0.000	0.000	-99.00	-99.00
Term Spklt - End Veg	11	20.3	11.3	12.4	12.01	80.5	27.0	0.000	0.000	0.014	0.014	-99.00	-99.00

```
 End Veg    - End Ear Gr    6  24.9  11.6  17.0  12.25    0.0   21.1  0.000  0.000  0.042  0.042 -99.00 -99.00
 End Ear Gr - Beg Gr Fil    7  28.2  13.8  19.5  12.43    0.0   24.0  0.000  0.000  0.000  0.000 -99.00 -99.00
 Beg Gr Fil - End Gr Fil   35  30.1  15.6  20.8  13.07    3.5  110.5  0.017  0.049  0.325  0.325 -99.00 -99.00

 Germinate  - End Gr Fil  141  22.5  10.1  15.1  11.90  261.3  280.8  0.004  0.012  0.084  0.084 -99.00 -99.00
--------------------------------------------------------------------------------------------------------------

*WATER PRODUCTIVITY

 Growing season length: 141 days

 Precipitation during growth season       261.3 mm[rain]
   Dry Matter Productivity                 3.97 kg[DM]/m3[rain]          =   39.7 kg[DM]/ha per mm[rain]
   Yield Productivity                      1.70 kg[grain yield]/m3[rain] =   17.0 kg[yield]/ha per mm[rain]

 Evapotranspiration during growth season   280.8 mm[ET]
   Dry Matter Productivity                 3.69 kg[DM]/m3[ET]            =   36.9 kg[DM]/ha per mm[ET]
   Yield Productivity                      1.58 kg[grain yield]/m3[ET]   =   15.8 kg[yield]/ha per mm[ET]

 Transpiration during growth season       196.5 mm[EP]
   Dry Matter Productivity                 5.27 kg[DM]/m3[EP]            =   52.7 kg[DM]/ha per mm[EP]
   Yield Productivity                      2.26 kg[grain yield]/m3[EP]   =   22.6 kg[yield]/ha per mm[EP]

--------------------------------------------------------------------------------------------------------------

         WHEAT YIELD :     4666 kg/ha    [Dry weight]

**************************************************************************************************************

*DSSAT Cropping System Model Ver. 4.5.0.030              AUG 01, 2015; 13:01:54

*RUN   2         : T1
 MODEL           : CSCER045 - Wheat
 EXPERIMENT      : TEST2012 WH TEST2011WH SUNI2011WH EFFECT OF ELEVATED CO2 ON WH
 TREATMENT  2    : T1


 CROP            : Wheat              CULTIVAR : PBW 343   (org)  ECOTYPE :INWH01
 STARTING DATE   : NOV 25 1911
 PLANTING DATE   : NOV 20 1912    PLANTS/m2 : 33.0     ROW SPACING :  20.cm
 WEATHER         : WRDM   1911
 SOIL            : IITR791201     TEXTURE : CL    - Dhanauri
 SOIL INITIAL C  : DEPTH:120cm EXTR. H2O:127.2mm  NO3: 46.2kg/ha  NH4:  5.3kg/ha
 WATER BALANCE   : IRRIGATE ON REPORTED DATE(S)
 IRRIGATION      :      210 mm IN     3 APPLICATIONS
 NITROGEN BAL.   : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER    :      120 kg/ha IN     3 APPLICATIONS
 RESIDUE/MANURE  : INITIAL :   100 kg/ha ;       0 kg/ha IN     0 APPLICATIONS
 ENVIRONM. OPT.  : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= A  0.00
                   RAIN= A  0.00  CO2 = A 100.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT  : WATER   :Y  NITROGEN:Y  N-FIX:N  PHOSPH :N  PESTS  :N
                   PHOTO   :C  ET      :R  INFIL:S  HYDROL :R  SOM    :G
                   CO2     :D  NSWIT   :1  EVAP :R  SOIL   :2
 MANAGEMENT OPT  : PLANTING:R  IRRIG   :R  FERT :R  RESIDUE:N  HARVEST:M
                   WEATHER :M  TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

   SOIL LOWER UPPER   SAT  EXTR  INIT   ROOT   BULK     pH    NO3    NH4    ORG
  DEPTH LIMIT LIMIT    SW    SW    SW   DIST   DENS                          C
   cm   cm3/cm3    cm3/cm3    cm3/cm3         g/cm3         ugN/g  ugN/g     %
--------------------------------------------------------------------------------
   0-  5 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
   5- 15 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  15- 30 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  30- 45 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
  45- 60 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
  60- 90 0.097 0.201 0.407 0.104 0.113   0.22   1.50   7.80   2.60   0.30   0.20
  90-120 0.082 0.195 0.419 0.113 0.099   0.12   1.42   7.80   2.60   0.30   0.00

TOT-120  12.1  24.8  49.4  12.7  14.0  <--cm   -  kg/ha-->  46.2    5.3  27000
SOIL ALBEDO    : 0.13      EVAPORATION LIMIT : 6.00        MIN. FACTOR  : 1.00
RUNOFF CURVE # :73.00      DRAINAGE RATE     : 0.40        FERT. FACTOR : 1.00

 Wheat      CULTIVAR :IN0013-PBW 343   (org)    ECOTYPE :INWH01
 P1V    :  20.000  P1D    : 70.0000  P5     :  800.00
```

G1 : 20.000 G2 : 45.000 G3 : 1.500 PHINT : 95.000

*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

...... DATE				GROWTH	BIOMASS	LEAF		CROP N		STRESS	
YEARDOY	DOM	MON	DAP	STAGE........	kg/ha	AREA	NUMBER	kg/ha	%	H2O	N
1912325	20	Nov	0	7 Sowing	0	0.00	0.0	0	0.0	0.00	0.00
1912326	21	Nov	1	8 Germinate	0	0.00	0.0	0	0.0	0.00	0.00
1912329	24	Nov	6	9 Emergence	0	0.00	0.0	0	0.0	0.00	0.00
1913045	14	Feb	86	1 Term Spklt	2911	1.48	11.5	48	1.8	0.00	0.00
1913056	25	Feb	97	2 End Veg	4378	3.22	13.3	68	1.7	0.00	0.02
1913062	1	Mar	101	3 End Ear Gr	5685	3.81	13.3	69	1.4	0.00	0.06
1913069	07	Mar	108	4 Beg Gr Fil	7453	1.81	13.3	69	1.1	0.00	0.00
1913104	06	Apr	138	5 End Gr Fil	11951	0.00	13.3	87	0.8	0.00	0.37
1913104	06	Apr	138	6 Harvest	11951	0.00	13.3	87	0.8	0.00	0.00

*MAIN GROWTH AND DEVELOPMENT VARIABLES

@ VARIABLE	SIMULATED	MEASURED
--------	---------	--------
Emergence (DAP)	6	-99
Anthesis (DAP)	99	-99
Maturity (DAP)	138	-99
Product wt (kg dm/ha;no loss)	4970	-99
Product unit weight (g dm)	0.039	-99.0
Product number (no/m2)	12744	-99
Product number (no/group)	39.0	-99.0
Product harvest index (ratio)	0.42	-99.00
Maximum leaf area index	3.8	-99.0
Final leaf number (one axis)	13.3	-99.0
Final shoot number (#/m2)	660	-99
Canopy (tops) wt (kg dm/ha)	11951	-99
Vegetative wt (kg dm/ha)	6981	0
Root wt (kg dm/ha)	489	-99
Assimilate wt (kg dm/ha)	12260	-99
Senesced wt (kg dm/ha)	502	-99
Reserves wt (kg dm/ha)	3889	-99
N uptake (kg/ha)	104.7	-99.0
N senesced (kg/ha)	11.9	-99.0
Above-ground N (kg/ha)	86.8	-99.0
Root N (kg/ha)	6.2	-99.0
Vegetative N (kg/ha)	9.9	-99.0
Product N (kg/ha)	76.9	-99.0
Product N harvest index (ratio)	0.89	-99.00
Product N (%)	1.6	-99.0
Vegetative N (%)	0.2	-99.0
Leaf+stem wt,anthesis (kg dm/ha)	5378	-99
Leaf+stem N,anthesis (kg/ha)	69.1	-99.0
Leaf N,anthesis (%)	4.3	-99.0

*ENVIRONMENTAL AND STRESS FACTORS

Development Phase	Environment: Average					Environment: Cumulative		Stress (0=Min, 1=Max Stress): Water		Nitrogen		Phosphorus	
	Time Span days	Temp Max øC	Temp Min øC	Solar Rad MJ/m2	Photop [day] hr	Rain mm	Evapo Trans mm	Photo synth	Growth	Photo synth	Growth	Photo synth	Growth
Germinate - Term Spklt	82	18.9	7.2	12.5	11.31	177.3	94.0	0.000	0.000	0.000	0.000	-99.00	-99.00
Term Spklt - End Veg	11	20.3	11.3	12.4	12.01	80.5	26.3	0.000	0.000	0.020	0.020	-99.00	-99.00
End Veg - End Ear Gr	6	24.9	11.6	17.0	12.25	0.0	20.6	0.000	0.000	0.057	0.057	-99.00	-99.00
End Ear Gr - Beg Gr Fil	7	28.2	13.8	19.5	12.43	0.0	23.3	0.000	0.000	0.000	0.000	-99.00	-99.00
Beg Gr Fil - End Gr Fil	35	30.1	15.6	20.8	13.07	3.5	106.9	0.004	0.024	0.373	0.373	-99.00	-99.00
Germinate - End Gr Fil	138	22.5	10.1	15.1	11.89	261.3	271.2	0.001	0.006	0.096	0.096	-99.00	-99.00

*WATER PRODUCTIVITY

Growing season length: 138 days

Precipitation during growth season 261.3 mm[rain]
Dry Matter Productivity 4.11 kg[DM]/m3[rain] = 41.1 kg[DM]/ha per mm[rain]

```
  Yield Productivity                     1.82 kg[grain yield]/m3[rain] =   18.2 kg[yield]/ha per mm[rain]

 Evapotranspiration during growth season   271.2 mm[ET]
   Dry Matter Productivity                3.96 kg[DM]/m3[ET]            =   39.6 kg[DM]/ha per mm[ET]
   Yield Productivity                     1.75 kg[grain yield]/m3[ET]   =   17.5 kg[yield]/ha per mm[ET]

 Transpiration during growth season       186.2 mm[EP]
   Dry Matter Productivity                5.77 kg[DM]/m3[EP]            =   57.7 kg[DM]/ha per mm[EP]
   Yield Productivity                     2.55 kg[grain yield]/m3[EP]   =   25.5 kg[yield]/ha per mm[EP]

------------------------------------------------------------------------------------------------------------

         WHEAT YIELD :     4970 kg/ha    [Dry weight]

************************************************************************************************************

*DSSAT Cropping System Model Ver. 4.5.0.030                AUG 01, 2015; 13:01:55

*RUN   3         : T2
 MODEL           : CSCER045 - Wheat
 EXPERIMENT      : TEST2012 WH TEST2011WH SUNI2011WH EFFECT OF ELEVATED CO2 ON WH
 TREATMENT  3    : T2


 CROP            : Wheat                CULTIVAR : PBW 343   (org)  ECOTYPE :INWH01
 STARTING DATE   : NOV 25 1911
 PLANTING DATE   : NOV 20 1912    PLANTS/m2 : 33.0     ROW SPACING :  20.cm
 WEATHER         : WRDM   1911
 SOIL            : IITR791201     TEXTURE : CL    - Dhanauri
 SOIL INITIAL C  : DEPTH:120cm EXTR. H2O:127.2mm  NO3: 46.2kg/ha  NH4:  5.3kg/ha
 WATER BALANCE   : IRRIGATE ON REPORTED DATE(S)
 IRRIGATION      :      210 mm IN      3 APPLICATIONS
 NITROGEN BAL.   : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER    :      120 kg/ha IN      3 APPLICATIONS
 RESIDUE/MANURE  : INITIAL :   100 kg/ha ;         0 kg/ha IN      0 APPLICATIONS
 ENVIRONM. OPT.  : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= A  0.00
                   RAIN= A  0.00  CO2 = A 200.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT  : WATER   :Y  NITROGEN:Y  N-FIX:N  PHOSPH :N  PESTS  :N
                   PHOTO   :C  ET      :R  INFIL:S  HYDROL :R  SOM    :G
                   CO2     :D  NSWIT   :1  EVAP :R  SOIL   :2
 MANAGEMENT OPT  : PLANTING:R  IRRIG   :R  FERT :R  RESIDUE:N  HARVEST:M
                   WEATHER :M  TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

   SOIL LOWER UPPER   SAT  EXTR  INIT   ROOT   BULK     pH    NO3    NH4    ORG
  DEPTH LIMIT LIMIT    SW    SW    SW   DIST   DENS                          C
   cm   cm3/cm3    cm3/cm3    cm3/cm3          g/cm3          ugN/g  ugN/g    %
--------------------------------------------------------------------------------
  0-  5 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  5- 15 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
 15- 30 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
 30- 45 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
 45- 60 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
 60- 90 0.097 0.201 0.407 0.104 0.113   0.22   1.50   7.80   2.60   0.30   0.20
 90-120 0.082 0.195 0.419 0.113 0.099   0.12   1.42   7.80   2.60   0.30   0.00

TOT-120  12.1  24.8  49.4  12.7  14.0  <--cm   -  kg/ha-->  46.2    5.3  27000
SOIL ALBEDO    : 0.13       EVAPORATION LIMIT : 6.00        MIN. FACTOR  : 1.00
RUNOFF CURVE # :73.00       DRAINAGE RATE     : 0.40        FERT. FACTOR : 1.00

 Wheat      CULTIVAR :IN0013-PBW 343   (org)    ECOTYPE :INWH01
 P1V    :  20.000  P1D    : 70.0000  P5     :  800.00
 G1     :  20.000  G2     :  45.000  G3     :   1.500  PHINT  :  95.000


*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

 ...... DATE ......  GROWTH       BIOMASS   LEAF       CROP N      STRESS
 YEARDOY DOM MON DAP STAGE........ kg/ha AREA NUMBER  kg/ha   %    H2O    N
 1912325  20 Nov   0 7 Sowing         0  0.00   0.0      0   0.0  0.00  0.00
 1912326  21 Nov   1 8 Germinate      0  0.00   0.0      0   0.0  0.00  0.00
 1912329  24 Nov   7 9 Emergence      0  0.00   0.0      0   0.0  0.00  0.00
 1913045  14 Feb  86 1 Term Spklt  3398  1.52  11.5     48   1.7  0.00  0.00
```

```
 1913056  25 Feb  97 2 End Veg     5222  3.48  13.3    67   1.6  0.00  0.03
 1913062   3 Mar 103 3 End Ear Gr  6831  3.61  13.3    69   1.3  0.00  0.07
 1913069  10 Mar 110 4 Beg Gr Fil  9013  1.86  13.3    69   1.0  0.00  0.00
 1913104  07 Apr 139 5 End Gr Fil 13707  0.00  13.3    87   0.8  0.00  0.42
 1913104  07 Apr 139 6 Harvest    13707  0.00  13.3    87   0.8  0.00  0.00

*MAIN GROWTH AND DEVELOPMENT VARIABLES

@     VARIABLE                          SIMULATED     MEASURED
      --------                          ---------     --------
      Emergence (DAP)                         7          -99
      Anthesis (DAP)                        098          -99
      Maturity (DAP)                        139          -99
      Product wt (kg dm/ha;no loss)        5684          -99
      Product unit weight (g dm)          0.041        -99.0
      Product number (no/m2)              13863          -99
      Product number (no/group)            41.2        -99.0
      Product harvest index (ratio)        0.41       -99.00
      Maximum leaf area index               3.6        -99.0
      Final leaf number (one axis)         13.3        -99.0
      Final shoot number (#/m2)             660          -99
      Canopy (tops) wt (kg dm/ha)         13707          -99
      Vegetative wt (kg dm/ha)             8023            0
      Root wt (kg dm/ha)                    521          -99
      Assimilate wt (kg dm/ha)            12742          -99
      Senesced wt (kg dm/ha)                525          -99
      Reserves wt (kg dm/ha)               3858          -99
      N uptake (kg/ha)                    105.2        -99.0
      N senesced (kg/ha)                   12.2        -99.0
      Above-ground N (kg/ha)               86.6        -99.0
      Root N (kg/ha)                        6.6        -99.0
      Vegetative N (kg/ha)                 10.1        -99.0
      Product N (kg/ha)                    76.5        -99.0
      Product N harvest index (ratio)      0.88       -99.00
      Product N (%)                         1.5        -99.0
      Vegetative N (%)                      0.2        -99.0
      Leaf+stem wt,anthesis (kg dm/ha)     5764          -99
      Leaf+stem N,anthesis (kg/ha)         68.7        -99.0
      Leaf N,anthesis (%)                   4.3        -99.0

*ENVIRONMENTAL AND STRESS FACTORS

 |-----Development Phase------|-------------Environment--------------|----------------Stress-----------------|
                              |--------Average-------|---Cumulative--|         (0=Min, 1=Max Stress)         |
                         Time  Temp  Temp Solar Photop         Evapo |----Water---|--Nitrogen--|--Phosphorus-|
                         Span   Max   Min   Rad  [day]   Rain  Trans  Photo         Photo         Photo
                         days    øC    øC MJ/m2     hr     mm     mm  synth Growth  synth Growth  synth Growth
--------------------------------------------------------------------------------------------------------------
 Germinate  - Term Spklt   82  18.9   7.2  12.5  11.31  177.3   90.1  0.000  0.000  0.000  0.000 -99.00 -99.00
 Term Spklt - End Veg      11  20.3  11.3  12.4  12.01   80.5   25.3  0.000  0.000  0.027  0.027 -99.00 -99.00
 End Veg    - End Ear Gr    6  24.9  11.6  17.0  12.25    0.0   20.1  0.000  0.000  0.074  0.074 -99.00 -99.00
 End Ear Gr - Beg Gr Fil    7  28.2  13.8  19.5  12.43    0.0   22.6  0.000  0.000  0.000  0.000 -99.00 -99.00
 Beg Gr Fil - End Gr Fil   35  30.1  15.6  20.8  13.07    3.5  103.1  0.000  0.002  0.420  0.420 -99.00 -99.00

 Germinate  - End Gr Fil  139  22.5  10.1  15.1  11.89  261.3  261.4  0.000  0.001  0.109  0.109 -99.00 -99.00
--------------------------------------------------------------------------------------------------------------

*WATER PRODUCTIVITY

 Growing season length: 139 days

 Precipitation during growth season        261.3 mm[rain]
   Dry Matter Productivity                  4.26 kg[DM]/m3[rain]          =   42.6 kg[DM]/ha per mm[rain]
   Yield Productivity                       1.95 kg[grain yield]/m3[rain] =   19.5 kg[yield]/ha per mm[rain]

 Evapotranspiration during growth season   261.4 mm[ET]
   Dry Matter Productivity                  4.26 kg[DM]/m3[ET]            =   42.6 kg[DM]/ha per mm[ET]
   Yield Productivity                       1.95 kg[grain yield]/m3[ET]   =   19.5 kg[yield]/ha per mm[ET]

 Transpiration during growth season        176.0 mm[EP]
   Dry Matter Productivity                  6.32 kg[DM]/m3[EP]            =   63.2 kg[DM]/ha per mm[EP]
   Yield Productivity                       2.90 kg[grain yield]/m3[EP]   =   29.0 kg[yield]/ha per mm[EP]

--------------------------------------------------------------------------------------------------------------

          WHEAT YIELD :     5684 kg/ha    [Dry weight]
```

```
*******************************************************************************************************

*DSSAT Cropping System Model Ver. 4.5.0.030            AUG 01, 2015; 13:01:55

*RUN   4        : T3
 MODEL          : CSCER045 - Wheat
 EXPERIMENT     : TEST2012 WH TEST2011WH SUNI2011WH EFFECT OF ELEVATED CO2 ON WH
 TREATMENT  4   : T3


 CROP           : Wheat            CULTIVAR : PBW 343   (org)  ECOTYPE :INWH01
 STARTING DATE  : NOV 25 1911
 PLANTING DATE  : NOV 20 1912    PLANTS/m2 : 33.0     ROW SPACING :  20.cm
 WEATHER        : WRDM   1911
 SOIL           : IITR791201     TEXTURE : CL    - Dhanauri
 SOIL INITIAL C : DEPTH:120cm EXTR. H2O:127.2mm  NO3: 46.2kg/ha  NH4:  5.3kg/ha
 WATER BALANCE  : IRRIGATE ON REPORTED DATE(S)
 IRRIGATION     :      210 mm IN     3 APPLICATIONS
 NITROGEN BAL.  : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER   :      120 kg/ha IN     3 APPLICATIONS
 RESIDUE/MANURE : INITIAL :   100 kg/ha ;       0 kg/ha IN     0 APPLICATIONS
 ENVIRONM. OPT. : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= A  0.00
                  RAIN= A  0.00  CO2 = A 300.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT : WATER   :Y  NITROGEN:Y  N-FIX:N  PHOSPH :N  PESTS  :N
                  PHOTO   :C  ET      :R  INFIL:S  HYDROL :R  SOM    :G
                  CO2     :D  NSWIT   :1  EVAP :R  SOIL   :2
 MANAGEMENT OPT : PLANTING:R  IRRIG   :R  FERT :R  RESIDUE:N  HARVEST:M
                  WEATHER :M  TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

   SOIL LOWER UPPER   SAT  EXTR  INIT   ROOT   BULK     pH    NO3    NH4    ORG
  DEPTH LIMIT LIMIT    SW    SW    SW   DIST   DENS                          C
   cm   cm3/cm3    cm3/cm3    cm3/cm3         g/cm3         ugN/g  ugN/g     %
--------------------------------------------------------------------------------
   0-  5 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
   5- 15 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  15- 30 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  30- 45 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
  45- 60 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
  60- 90 0.097 0.201 0.407 0.104 0.113   0.22   1.50   7.80   2.60   0.30   0.20
  90-120 0.082 0.195 0.419 0.113 0.099   0.12   1.42   7.80   2.60   0.30   0.00

TOT-120  12.1  24.8  49.4  12.7  14.0  <--cm   -  kg/ha-->  46.2    5.3  27000
SOIL ALBEDO    : 0.13      EVAPORATION LIMIT : 6.00        MIN. FACTOR  : 1.00
RUNOFF CURVE # :73.00      DRAINAGE RATE     : 0.40        FERT. FACTOR : 1.00

 Wheat      CULTIVAR :IN0013-PBW 343   (org)    ECOTYPE :INWH01
 P1V    :  20.000  P1D    : 70.0000  P5     :  800.00
 G1     :  20.000  G2     :  45.000  G3     :   1.500  PHINT  :  95.000


*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

 ...... DATE ......  GROWTH       BIOMASS   LEAF       CROP N      STRESS
 YEARDOY DOM MON DAP STAGE........ kg/ha AREA NUMBER  kg/ha   %    H2O    N
 1912325  20 Nov   0 7 Sowing         0  0.00   0.0      0  0.0  0.00  0.00
 1912326  21 Nov   1 8 Germinate      0  0.00   0.0      0  0.0  0.00  0.00
 1912329  24 Nov   8 9 Emergence      0  0.00   0.0      0  0.0  0.00  0.00
 1913045  14 Feb  86 1 Term Spklt  3776  1.58  11.5     48  1.6  0.00  0.00
 1913056  25 Feb  97 2 End Veg     5857  3.52  13.3     66  1.5  0.00  0.03
 1913062   3 Mar 103 3 End Ear Gr  7692  3.60  13.3     69  1.2  0.00  0.09
 1913069  12 Mar 112 4 Beg Gr Fil 10160  1.87  13.3     68  0.9  0.00  0.00
 1913104  07 Apr 139 5 End Gr Fil 14958  0.00  13.3     86  0.8  0.00  0.46
 1913104  07 Apr 139 6 Harvest    14958  0.00  13.3     86  0.8  0.00  0.00

*MAIN GROWTH AND DEVELOPMENT VARIABLES

@     VARIABLE                          SIMULATED     MEASURED
      --------                          ---------     --------
      Emergence (DAP)                        8          -99
      Anthesis (DAP)                       098          -99
```

Maturity (DAP)	139	-99
Product wt (kg dm/ha;no loss)	5900	-99
Product unit weight (g dm)	0.042	-99.0
Product number (no/m2)	14048	-99
Product number (no/group)	40.3	-99.0
Product harvest index (ratio)	0.39	-99.00
Maximum leaf area index	3.6	-99.0
Final leaf number (one axis)	13.3	-99.0
Final shoot number (#/m2)	660	-99
Canopy (tops) wt (kg dm/ha)	14958	-99
Vegetative wt (kg dm/ha)	9058	0
Root wt (kg dm/ha)	550	-99
Assimilate wt (kg dm/ha)	13177	-99
Senesced wt (kg dm/ha)	546	-99
Reserves wt (kg dm/ha)	3830	-99
N uptake (kg/ha)	105.5	-99.0
N senesced (kg/ha)	12.5	-99.0
Above-ground N (kg/ha)	86.2	-99.0
Root N (kg/ha)	6.9	-99.0
Vegetative N (kg/ha)	10.2	-99.0
Product N (kg/ha)	76.0	-99.0
Product N harvest index (ratio)	0.88	-99.00
Product N (%)	1.4	-99.0
Vegetative N (%)	0.2	-99.0
Leaf+stem wt,anthesis (kg dm/ha)	6116	-99
Leaf+stem N,anthesis (kg/ha)	68.3	-99.0
Leaf N,anthesis (%)	4.3	-99.0

*ENVIRONMENTAL AND STRESS FACTORS

Development Phase	Environment: Average: Time Span days	Temp Max øC	Temp Min øC	Solar Rad MJ/m2	Photop [day] hr	Cumulative: Rain mm	Evapo Trans mm	Stress (0=Min, 1=Max Stress): Water Photo synth	Water Growth	Nitrogen Photo synth	Nitrogen Growth	Phosphorus Photo synth	Phosphorus Growth
Germinate - Term Spklt	82	18.9	7.2	12.5	11.31	177.3	86.7	0.000	0.000	0.000	0.000	-99.00	-99.00
Term Spklt - End Veg	11	20.3	11.3	12.4	12.01	80.5	24.4	0.000	0.000	0.032	0.032	-99.00	-99.00
End Veg - End Ear Gr	6	24.9	11.6	17.0	12.25	0.0	19.5	0.000	0.000	0.091	0.091	-99.00	-99.00
End Ear Gr - Beg Gr Fil	7	28.2	13.8	19.5	12.43	0.0	22.0	0.000	0.000	0.000	0.000	-99.00	-99.00
Beg Gr Fil - End Gr Fil	35	30.1	15.6	20.8	13.07	3.5	99.6	0.000	0.000	0.459	0.459	-99.00	-99.00
Germinate - End Gr Fil	139	22.5	10.1	15.1	11.89	261.3	252.3	0.000	0.000	0.120	0.120	-99.00	-99.00

*WATER PRODUCTIVITY

Growing season length: 139 days

Precipitation during growth season	261.3 mm[rain]		
Dry Matter Productivity	4.39 kg[DM]/m3[rain]	=	43.9 kg[DM]/ha per mm[rain]
Yield Productivity	2.07 kg[grain yield]/m3[rain]	=	20.7 kg[yield]/ha per mm[rain]
Evapotranspiration during growth season	252.3 mm[ET]		
Dry Matter Productivity	4.55 kg[DM]/m3[ET]	=	45.5 kg[DM]/ha per mm[ET]
Yield Productivity	2.15 kg[grain yield]/m3[ET]	=	21.5 kg[yield]/ha per mm[ET]
Transpiration during growth season	166.4 mm[EP]		
Dry Matter Productivity	6.90 kg[DM]/m3[EP]	=	69.0 kg[DM]/ha per mm[EP]
Yield Productivity	3.26 kg[grain yield]/m3[EP]	=	32.6 kg[yield]/ha per mm[EP]

WHEAT YIELD : 5900 kg/ha [Dry weight]

****

Annexure-3

DSSAT 4.5 Simulation file 2013-14 (Model calibration using different sowing dates)

```
*SIMULATION OVERVIEW FILE


*DSSAT Cropping System Model Ver. 4.5.0.030          JUN 18, 2016; 01:43:01

*RUN   1        : D1
 MODEL          : CSCER045 - Wheat
 EXPERIMENT     : PBWD1343 WH TEST2012WH TEST2011WH SUNI2011WH EFFECT OF ELEVATE
 TREATMENT  1   : D1


 CROP           : Wheat              CULTIVAR : PBW 343   (org)  ECOTYPE :INWH01
 STARTING DATE  : NOV 15 1913
 PLANTING DATE  : NOV 15 1913    PLANTS/m2 : 33.0     ROW SPACING :  20.cm
 WEATHER        : WRDM   1913
 SOIL           : IITR791201     TEXTURE : CL    - Dhanauri
 SOIL INITIAL C : DEPTH:120cm EXTR. H2O:127.2mm  NO3: 46.2kg/ha  NH4:  5.3kg/ha
 WATER BALANCE  : AUTOMATIC IRRIGATION - REFILL PROFILE
 IRRIGATION     : AUTOMATIC - PLANTING -> MATURITY [ SOIL DEPTH:30.00m 50.%]
 NITROGEN BAL.  : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER   :      120 kg/ha IN     3 APPLICATIONS
 RESIDUE/MANURE : INITIAL :   100 kg/ha ;        0 kg/ha IN     0 APPLICATIONS
 ENVIRONM. OPT. : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= A  0.00
                  RAIN= A  0.00  CO2 = A   0.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT : WATER   :Y  NITROGEN:Y  N-FIX:N  PHOSPH :N  PESTS  :N
                  PHOTO   :C  ET      :R  INFIL:S  HYDROL :R  SOM    :G
                  CO2     :D  NSWIT   :1  EVAP :R  SOIL   :2
 MANAGEMENT OPT : PLANTING:R  IRRIG   :A  FERT :R  RESIDUE:N  HARVEST:M
                  WEATHER :M  TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

   SOIL LOWER UPPER   SAT  EXTR  INIT   ROOT   BULK     pH    NO3    NH4    ORG
  DEPTH LIMIT LIMIT    SW    SW    SW   DIST   DENS                          C
   cm   cm3/cm3    cm3/cm3    cm3/cm3          g/cm3          ugN/g  ugN/g    %
--------------------------------------------------------------------------------
   0-  5 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
   5- 15 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  15- 30 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  30- 45 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
  45- 60 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
  60- 90 0.097 0.201 0.407 0.104 0.113   0.22   1.50   7.80   2.60   0.30   0.20
  90-120 0.082 0.195 0.419 0.113 0.099   0.12   1.42   7.80   2.60   0.30   0.00

TOT-120  12.1  24.8  49.4  12.7  14.0  <--cm   -  kg/ha-->  46.2    5.3  27000
SOIL ALBEDO    : 0.13      EVAPORATION LIMIT : 6.00        MIN. FACTOR  : 1.00
RUNOFF CURVE # :73.00      DRAINAGE RATE     : 0.40        FERT. FACTOR : 1.00

 Wheat      CULTIVAR :IN0013-PBW 343   (org)    ECOTYPE :INWH01
 P1V    :  20.000  P1D    : 70.0000  P5     :  800.00
 G1     :  20.000  G2     :  45.000  G3     :   1.500  PHINT  :  95.000


*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

 ...... DATE ......  GROWTH        BIOMASS   LEAF       CROP N      STRESS
 YEARDOY DOM MON DAP STAGE........ kg/ha AREA NUMBER  kg/ha   %    H2O    N
 1913320  15 Nov   0 7 Sowing          0  0.00   0.0      0   0.0  0.00  0.00
 1913321  16 Nov   1 8 Germinate       0  0.00   0.0      0   0.0  0.00  0.00
 1913324  21 Nov   6 9 Emergence       0  0.00   0.0      0   0.0  0.00  0.00
 1914042  11 Feb  88 1 Term Spklt   2684  1.49  11.9     51   1.9  0.00  0.00
 1914053  21 Feb  97 2 End Veg      3960  2.80  13.7     75   1.9  0.00  0.00
 1914059  28 Feb 105 3 End Ear Gr   4802  1.99  13.7     75   1.6  0.00  0.01
 1914067   8 Mar 113 4 Beg Gr Fil   6481  1.78  13.7     75   1.2  0.00  0.00
 1914102  12 Apr 148 5 End Gr Fil  10900  0.00  13.7     92   0.8  0.00  0.32
 1914102  12 Apr 148 6 Harvest     10900  0.00  13.7     92   0.8  0.00  0.00
```

BIOMASS = Above-ground dry weight (kg/ha)
LEAF AREA = Leaf area index (m2/m2)
LEAF NUMBER = Leaf number produced on main axis
CROP N = Above-ground N (kg/ha)
CROP N% = Above-ground N concentration (%)
H2O STRESS = Photosynthesis stress,average (0-1,0=none)
N STRESS = Photosynthesis stress,average (0-1,0=none)

*MAIN GROWTH AND DEVELOPMENT VARIABLES

@ VARIABLE	SIMULATED	MEASURED
Emergence (DAP)	6	-99
Anthesis (DAP)	98	-99
Maturity (DAP)	148	-99
Product wt (kg dm/ha;no loss)	4774	-99
Product unit weight (g dm)	0.045	-99.0
Product number (no/m2)	10608	-99
Product number (no/group)	16.1	-99.0
Product harvest index (ratio)	0.44	-99.00
Maximum leaf area index	2.8	-99.0
Final leaf number (one axis)	13.7	-99.0
Final shoot number (#/m2)	361	-99
Canopy (tops) wt (kg dm/ha)	10900	-99
Vegetative wt (kg dm/ha)	6126	0
Root wt (kg dm/ha)	483	-99
Assimilate wt (kg dm/ha)	12454	-99
Senesced wt (kg dm/ha)	539	-99
Reserves wt (kg dm/ha)	4026	-99
N uptake (kg/ha)	111.3	-99.0
N senesced (kg/ha)	13.3	-99.0
Above-ground N (kg/ha)	92.2	-99.0
Root N (kg/ha)	6.1	-99.0
Vegetative N (kg/ha)	10.2	-99.0
Product N (kg/ha)	82.0	-99.0
Product N harvest index (ratio)	0.89	-99.00
Product N (%)	1.7	-99.0
Vegetative N (%)	0.2	-99.0
Leaf+stem wt,anthesis (kg dm/ha)	5196	-99
Leaf+stem N,anthesis (kg/ha)	75.1	-99.0
Leaf N,anthesis (%)	4.3	-99.0

Seed N must be added to N uptake to obtain a
balance with N in above-ground plus root material

Measured data are obtained from the A file,either
directly or by calculation from other other variables
using the expressions given below:

```
Product wt       Harvest wt (HWAH) / (Harvest%/100) (HPC)
Canopy wt        Grain wt (HWAM) + vegetative wt (VWAM)
Vegetative wt    Canopy wt (CWAM) - grain wt (HWAM)
  = leaf+stem+retained dead material
Product unit wt  Grain yield (HWAM)/grain number (G#AM)
Product #/area   Product#/tiller (H#SM) *
                                  tiller number (T#AM)
Product #/group  Product#/area (H#AM) /
                              tiller number (T#AM)
Harvest index    Product wt (HWAM)/Canopy wt.(CWAM)
```

The same procedure is followed for nitrogen aspects

*ENVIRONMENTAL AND STRESS FACTORS

```
 |-----Development Phase------|-------------Environment--------------|----------------Stress-----------------|
                              |--------Average-------|---Cumulative--|         (0=Min, 1=Max Stress)         |
                         Time  Temp  Temp Solar Photop         Evapo |----Water---|--Nitrogen--|--Phosphorus-|
                         Span   Max   Min   Rad  [day]   Rain  Trans  Photo         Photo         Photo
                         days    øC    øC MJ/m2     hr     mm     mm  synth Growth  synth Growth  synth Growth
--------------------------------------------------------------------------------------------------------------
 Germinate  - Term Spklt   84  19.0   7.3  12.7  11.29  131.3  122.1  0.000  0.000  0.000  0.000 -99.00 -99.00
 Term Spklt - End Veg      11  20.9  10.4  13.4  11.94   80.5   29.4  0.000  0.000  0.003  0.003 -99.00 -99.00
```

```
 End Veg    - End Ear Gr    6  23.2  12.0  13.9  12.16    0.0   17.3  0.000  0.000  0.011  0.011 -99.00 -99.00
 End Ear Gr - Beg Gr Fil    8  26.8  12.5  19.4  12.36    0.0   33.3  0.000  0.000  0.000  0.000 -99.00 -99.00
 Beg Gr Fil - End Gr Fil   35  29.9  15.5  20.5  13.01    3.5  154.1  0.000  0.000  0.320  0.320 -99.00 -99.00

 Germinate  - End Gr Fil  144  22.4  10.0  15.1  11.85  215.1  356.2  0.000  0.000  0.078  0.078 -99.00 -99.00
--------------------------------------------------------------------------------------------------------------

*WATER PRODUCTIVITY

 Growing season length: 148 days

 Precipitation during growth season        215.1 mm[rain]
   Dry Matter Productivity                  4.17 kg[DM]/m3[rain]          =   41.7 kg[DM]/ha per mm[rain]
   Yield Productivity                       1.83 kg[grain yield]/m3[rain] =   18.3 kg[yield]/ha per mm[rain]

 Evapotranspiration during growth season   356.2 mm[ET]
   Dry Matter Productivity                  3.06 kg[DM]/m3[ET]            =   30.6 kg[DM]/ha per mm[ET]
   Yield Productivity                       1.34 kg[grain yield]/m3[ET]   =   13.4 kg[yield]/ha per mm[ET]

 Transpiration during growth season        203.6 mm[EP]
   Dry Matter Productivity                  5.35 kg[DM]/m3[EP]            =   53.5 kg[DM]/ha per mm[EP]
   Yield Productivity                       2.34 kg[grain yield]/m3[EP]   =   23.4 kg[yield]/ha per mm[EP]

--------------------------------------------------------------------------------------------------------------

          WHEAT YIELD :     4774 kg/ha    [Dry weight]

**************************************************************************************************************


*DSSAT Cropping System Model Ver. 4.5.0.030              JUN 18, 2016; 01:43:02

*RUN   2         : D2
 MODEL           : CSCER045 - Wheat
 EXPERIMENT      : PBWD1343 WH TEST2012WH TEST2011WH SUNI2011WH EFFECT OF ELEVATE
 TREATMENT  2    : D2


 CROP            : Wheat              CULTIVAR : PBW 343    (org)  ECOTYPE :INWH01
 STARTING DATE   : NOV 22 1913
 PLANTING DATE   : NOV 22 1913    PLANTS/m2 : 33.0     ROW SPACING :  20.cm
 WEATHER         : WRDM   1913
 SOIL            : IITR791201     TEXTURE : CL    - Dhanauri
 SOIL INITIAL C  : DEPTH:120cm EXTR. H2O:127.2mm  NO3: 46.2kg/ha  NH4:  5.3kg/ha
 WATER BALANCE   : AUTOMATIC IRRIGATION - REFILL PROFILE
 IRRIGATION      : AUTOMATIC - PLANTING -> MATURITY [ SOIL DEPTH:30.00m 50.%]
 NITROGEN BAL.   : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER    :      120 kg/ha IN      3 APPLICATIONS
 RESIDUE/MANURE  : INITIAL :   100 kg/ha ;        0 kg/ha IN      0 APPLICATIONS
 ENVIRONM. OPT.  : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= A  0.00
                   RAIN= A  0.00  CO2 = A   0.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT  : WATER   :Y  NITROGEN:Y  N-FIX:N  PHOSPH :N  PESTS  :N
                   PHOTO   :C  ET      :R  INFIL:S  HYDROL :R  SOM    :G
                   CO2     :D  NSWIT   :1  EVAP :R  SOIL   :2
 MANAGEMENT OPT  : PLANTING:R  IRRIG   :A  FERT :R  RESIDUE:N  HARVEST:M
                   WEATHER :M  TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

   SOIL LOWER UPPER   SAT  EXTR  INIT   ROOT   BULK     pH    NO3    NH4    ORG
  DEPTH LIMIT LIMIT    SW    SW    SW   DIST   DENS                          C
   cm   cm3/cm3    cm3/cm3   cm3/cm3         g/cm3         ugN/g  ugN/g     %
--------------------------------------------------------------------------------
   0-  5 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
   5- 15 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  15- 30 0.121 0.224 0.414 0.103 0.136   1.00   1.50   7.80   2.60   0.30   0.20
  30- 45 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
  45- 60 0.104 0.208 0.406 0.104 0.120   0.41   1.50   7.80   2.60   0.30   0.20
  60- 90 0.097 0.201 0.407 0.104 0.113   0.22   1.50   7.80   2.60   0.30   0.20
  90-120 0.082 0.195 0.419 0.113 0.099   0.12   1.42   7.80   2.60   0.30   0.00

TOT-120  12.1  24.8  49.4  12.7  14.0  <--cm   -  kg/ha-->   46.2    5.3  27000
SOIL ALBEDO    : 0.13      EVAPORATION LIMIT : 6.00         MIN. FACTOR  : 1.00
RUNOFF CURVE # :73.00      DRAINAGE RATE     : 0.40         FERT. FACTOR : 1.00
```

Wheat CULTIVAR :IN0013-PBW 343 (org) ECOTYPE :INWH01
P1V : 20.000 P1D : 70.0000 P5 : 800.00
G1 : 20.000 G2 : 45.000 G3 : 1.500 PHINT : 95.000

*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

...... DATE				GROWTH	BIOMASS	LEAF		CROP N		STRESS	
YEARDOY	DOM	MON	DAP	STAGE........	kg/ha	AREA	NUMBER	kg/ha	%	H2O	N
1913327	22	Nov	0	7 Sowing	0	0.00	0.0	0	0.0	0.00	0.00
1913328	23	Nov	1	8 Germinate	0	0.00	0.0	0	0.0	0.00	0.00
1913331	28	Nov	6	9 Emergence	0	0.00	0.0	0	0.0	0.00	0.00
1914046	15	Feb	85	1 Term Spklt	2350	1.41	11.3	48	2.0	0.00	0.00
1914057	26	Feb	96	2 End Veg	3572	2.90	13.2	74	2.1	0.00	0.00
1914063	4	Mar	102	3 End Ear Gr	4645	1.93	13.2	74	1.6	0.00	0.01
1914070	11	Mar	109	4 Beg Gr Fil	6102	1.74	13.2	74	1.2	0.00	0.00
1914105	15	Apr	144	5 End Gr Fil	11082	0.00	13.2	89	0.8	0.00	0.30
1914105	15	Apr	144	6 Harvest	11082	0.00	13.2	89	0.8	0.00	0.00

*MAIN GROWTH AND DEVELOPMENT VARIABLES

@ VARIABLE	SIMULATED	MEASURED
--------	---------	--------
Emergence (DAP)	6	-99
Anthesis (DAP)	98	-99
Maturity (DAP)	144	-99
Product wt (kg dm/ha;no loss)	4728	-99
Product unit weight (g dm)	0.045	-99.0
Product number (no/m2)	10506	-99
Product number (no/group)	29.0	-99.0
Product harvest index (ratio)	0.43	-99.00
Maximum leaf area index	2.9	-99.0
Final leaf number (one axis)	13.2	-99.0
Final shoot number (#/m2)	362	-99
Canopy (tops) wt (kg dm/ha)	11082	-99
Vegetative wt (kg dm/ha)	6354	0
Root wt (kg dm/ha)	458	-99
Assimilate wt (kg dm/ha)	12005	-99
Senesced wt (kg dm/ha)	465	-99
Reserves wt (kg dm/ha)	4017	-99
N uptake (kg/ha)	105.5	-99.0
N senesced (kg/ha)	11.1	-99.0
Above-ground N (kg/ha)	88.8	-99.0
Root N (kg/ha)	5.8	-99.0
Vegetative N (kg/ha)	10.0	-99.0
Product N (kg/ha)	78.8	-99.0
Product N harvest index (ratio)	0.89	-99.00
Product N (%)	1.8	-99.0
Vegetative N (%)	0.2	-99.0
Leaf+stem wt,anthesis (kg dm/ha)	4852	-99
Leaf+stem N,anthesis (kg/ha)	73.8	-99.0
Leaf N,anthesis (%)	4.4	-99.0

*ENVIRONMENTAL AND STRESS FACTORS

-----Development Phase------	--------------Environment--------------						-----------------Stress-----------------					
	--------Average-------				---Cumulative--		(0=Min, 1=Max Stress)					
	Time Span days	Temp Max øC	Temp Min øC	Solar Rad MJ/m2	Photop [day] hr	Rain mm	Evapo Trans mm	----Water--- Photo synth	Growth	--Nitrogen-- Photo synth	Growth	--Phosphorus- Photo synth	Growth
Germinate - Term Spklt	81	18.8	7.2	12.4	11.31	161.3	103.7	0.000	0.000	0.000	0.000	-99.00	-99.00
Term Spklt - End Veg	11	20.9	11.0	13.0	12.04	50.5	29.0	0.000	0.000	0.002	0.002	-99.00	-99.00
End Veg - End Ear Gr	6	25.4	12.0	17.7	12.27	0.0	22.3	0.000	0.000	0.005	0.005	-99.00	-99.00
End Ear Gr - Beg Gr Fil	7	28.5	14.3	19.4	12.46	0.0	30.3	0.000	0.000	0.000	0.000	-99.00	-99.00
Beg Gr Fil - End Gr Fil	35	30.2	15.7	20.9	13.11	3.5	153.6	0.000	0.000	0.296	0.296	-99.00	-99.00
Germinate - End Gr Fil	141	22.6	10.2	15.2	11.91	215.3	338.9	0.000	0.000	0.074	0.074	-99.00	-99.00

*WATER PRODUCTIVITY

Growing season length: 144 days

```
 Precipitation during growth season       215.3 mm[rain]
   Dry Matter Productivity                 4.05 kg[DM]/m3[rain]          =   40.5 kg[DM]/ha per mm[rain]
   Yield Productivity                      1.71 kg[grain yield]/m3[rain] =   17.1 kg[yield]/ha per mm[rain]

 Evapotranspiration during growth season  338.9 mm[ET]
   Dry Matter Productivity                 3.13 kg[DM]/m3[ET]            =   31.3 kg[DM]/ha per mm[ET]
   Yield Productivity                      1.32 kg[grain yield]/m3[ET]   =   13.2 kg[yield]/ha per mm[ET]

 Transpiration during growth season       199.3 mm[EP]
   Dry Matter Productivity                 5.32 kg[DM]/m3[EP]            =   53.2 kg[DM]/ha per mm[EP]
   Yield Productivity                      2.25 kg[grain yield]/m3[EP]   =   22.5 kg[yield]/ha per mm[EP]

------------------------------------------------------------------------------------------------------------

          WHEAT YIELD :     4728 kg/ha    [Dry weight]

************************************************************************************************************


*DSSAT Cropping System Model Ver. 4.5.0.030               JUN 18, 2016; 01:43:02

*RUN   3         : D3
 MODEL           : CSCER045 - Wheat
 EXPERIMENT      : PBWD1343 WH TEST2012WH TEST2011WH SUNI2011WH EFFECT OF ELEVATE
 TREATMENT  3    : D3


 CROP            : Wheat              CULTIVAR : PBW 343   (org)  ECOTYPE :INWH01
 STARTING DATE   : NOV 29 1913
 PLANTING DATE   : NOV 29 1913    PLANTS/m2 : 33.0     ROW SPACING :  20.cm
 WEATHER         : WRDM   1913
 SOIL            : IITR791201     TEXTURE : CL    - Dhanauri
 SOIL INITIAL C  : DEPTH:120cm EXTR. H2O:127.2mm  NO3: 46.2kg/ha  NH4:  5.3kg/ha
 WATER BALANCE   : AUTOMATIC IRRIGATION - REFILL PROFILE
 IRRIGATION      : AUTOMATIC - PLANTING -> MATURITY [ SOIL DEPTH:30.00m 50.%]
 NITROGEN BAL.   : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER    :      120 kg/ha IN     3 APPLICATIONS
 RESIDUE/MANURE  : INITIAL :   100 kg/ha ;       0 kg/ha IN     0 APPLICATIONS
 ENVIRONM. OPT.  : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= A  0.00
                   RAIN= A  0.00  CO2 = A   0.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT  : WATER    :Y  NITROGEN:Y  N-FIX:N  PHOSPH :N  PESTS  :N
                   PHOTO    :C  ET      :R  INFIL:S  HYDROL :R  SOM    :G
                   CO2      :D  NSWIT   :1  EVAP :R  SOIL   :2
 MANAGEMENT OPT  : PLANTING:R  IRRIG   :A  FERT :R  RESIDUE:N  HARVEST:M
                   WEATHER :M  TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS
```

SOIL DEPTH cm	LOWER LIMIT cm3/cm3	UPPER LIMIT	SAT SW cm3/cm3	EXTR SW	INIT SW cm3/cm3	ROOT DIST	BULK DENS g/cm3	pH	NO3 ugN/g	NH4 ugN/g	ORG C %
0- 5	0.121	0.224	0.414	0.103	0.136	1.00	1.50	7.80	2.60	0.30	0.20
5- 15	0.121	0.224	0.414	0.103	0.136	1.00	1.50	7.80	2.60	0.30	0.20
15- 30	0.121	0.224	0.414	0.103	0.136	1.00	1.50	7.80	2.60	0.30	0.20
30- 45	0.104	0.208	0.406	0.104	0.120	0.41	1.50	7.80	2.60	0.30	0.20
45- 60	0.104	0.208	0.406	0.104	0.120	0.41	1.50	7.80	2.60	0.30	0.20
60- 90	0.097	0.201	0.407	0.104	0.113	0.22	1.50	7.80	2.60	0.30	0.20
90-120	0.082	0.195	0.419	0.113	0.099	0.12	1.42	7.80	2.60	0.30	0.00

```
TOT-120  12.1  24.8  49.4  12.7  14.0  <--cm   -  kg/ha-->  46.2    5.3  27000
SOIL ALBEDO    : 0.13      EVAPORATION LIMIT : 6.00         MIN. FACTOR  : 1.00
RUNOFF CURVE # :73.00      DRAINAGE RATE     : 0.40         FERT. FACTOR : 1.00

 Wheat      CULTIVAR :IN0013-PBW 343   (org)    ECOTYPE :INWH01
 P1V    :  20.000  P1D    : 70.0000  P5     :  800.00
 G1     :  20.000  G2     :  45.000  G3     :   1.500  PHINT  :  95.000


*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

 ...... DATE ......  GROWTH       BIOMASS   LEAF       CROP N      STRESS
 YEARDOY DOM MON DAP STAGE........ kg/ha AREA NUMBER  kg/ha   %   H2O    N
```

1913334	29 Nov	0	7	Sowing	0	0.00	0.0	0	0.0	0.00	0.00
1913335	30 Nov	1	8	Germinate	0	0.00	0.0	0	0.0	0.00	0.00
1913338	7 Dec	7	9	Emergence	0	0.00	0.0	0	0.0	0.00	0.00
1914050	19 Feb	82	1	Term Spklt	1997	1.25	10.8	43	2.1	0.00	0.00
1914060	1 Mar	92	2	End Veg	3151	2.71	12.6	69	2.2	0.00	0.00
1914065	6 Mar	97	3	End Ear Gr	4112	1.77	12.6	69	1.7	0.00	0.00
1914072	13 Mar	104	4	Beg Gr Fil	5493	1.59	12.6	68	1.2	0.00	0.00
1914107	17 Apr	139	5	End Gr Fil	9964	0.00	12.6	82	0.8	0.00	0.28
1914107	17 Apr	139	6	Harvest	9964	0.00	12.6	82	0.8	0.00	0.00

*MAIN GROWTH AND DEVELOPMENT VARIABLES

@ VARIABLE	SIMULATED	MEASURED
Emergence (DAP)	7	-99
Anthesis (DAP)	96	-99
Maturity (DAP)	139	-99
Product wt (kg dm/ha;no loss)	4151	-99
Product unit weight (g dm)	0.045	-99.0
Product number (no/m2)	9225	-99
Product number (no/group)	27.2	-99.0
Product harvest index (ratio)	0.42	-99.00
Maximum leaf area index	2.7	-99.0
Final leaf number (one axis)	12.6	-99.0
Final shoot number (#/m2)	339	-99
Canopy (tops) wt (kg dm/ha)	9964	-99
Vegetative wt (kg dm/ha)	5813	0
Root wt (kg dm/ha)	425	-99
Assimilate wt (kg dm/ha)	11231	-99
Senesced wt (kg dm/ha)	401	-99
Reserves wt (kg dm/ha)	3788	-99
N uptake (kg/ha)	96.6	-99.0
N senesced (kg/ha)	9.5	-99.0
Above-ground N (kg/ha)	81.9	-99.0
Root N (kg/ha)	5.3	-99.0
Vegetative N (kg/ha)	9.2	-99.0
Product N (kg/ha)	72.7	-99.0
Product N harvest index (ratio)	0.89	-99.00
Product N (%)	1.8	-99.0
Vegetative N (%)	0.2	-99.0
Leaf+stem wt,anthesis (kg dm/ha)	4496	-99
Leaf+stem N,anthesis (kg/ha)	68.3	-99.0
Leaf N,anthesis (%)	4.3	-99.0

*ENVIRONMENTAL AND STRESS FACTORS

Development Phase	Environment: Average: Time Span days	Temp Max øC	Temp Min øC	Solar Rad MJ/m2	Photop [day] hr	Cumulative: Rain mm	Evapo Trans mm	Stress (0=Min, 1=Max Stress): Water Photo synth	Water Growth	Nitrogen Photo synth	Nitrogen Growth	Phosphorus Photo synth	Phosphorus Growth
Germinate - Term Spklt	78	18.4	7.3	12.1	11.35	190.8	106.5	0.000	0.000	0.000	0.000	-99.00	-99.00
Term Spklt - End Veg	10	22.9	11.8	14.2	12.13	8.5	29.2	0.000	0.000	0.000	0.000	-99.00	-99.00
End Veg - End Ear Gr	5	27.0	12.2	19.7	12.35	0.0	21.5	0.000	0.000	0.000	0.000	-99.00	-99.00
End Ear Gr - Beg Gr Fil	7	28.7	14.7	19.3	12.52	0.0	29.9	0.000	0.000	0.000	0.000	-99.00	-99.00
Beg Gr Fil - End Gr Fil	35	30.5	16.0	21.1	13.17	3.5	159.1	0.000	0.000	0.284	0.284	-99.00	-99.00
Germinate - End Gr Fil	136	22.7	10.4	15.3	11.97	201.8	346.2	0.000	0.000	0.073	0.073	-99.00	-99.00

*WATER PRODUCTIVITY

Growing season length: 139 days

Precipitation during growth season 201.8 mm[rain]
Dry Matter Productivity 3.82 kg[DM]/m3[rain] = 38.2 kg[DM]/ha per mm[rain]
Yield Productivity 1.59 kg[grain yield]/m3[rain] = 15.9 kg[yield]/ha per mm[rain]

Evapotranspiration during growth season 346.2 mm[ET]
Dry Matter Productivity 2.88 kg[DM]/m3[ET] = 28.8 kg[DM]/ha per mm[ET]
Yield Productivity 1.20 kg[grain yield]/m3[ET] = 12.0 kg[yield]/ha per mm[ET]

Transpiration during growth season 188.3 mm[EP]
Dry Matter Productivity 5.29 kg[DM]/m3[EP] = 52.9 kg[DM]/ha per mm[EP]
Yield Productivity 2.20 kg[grain yield]/m3[EP] = 22.0 kg[yield]/ha per mm[EP]

```
--------------------------------------------------------------------------------------------------------------------

         WHEAT YIELD :     4151 kg/ha    [Dry weight]

********************************************************************************************************************

*DSSAT Cropping System Model Ver. 4.5.0.030             JUN 18, 2016; 01:43:02

*RUN   4         : D4
 MODEL           : CSCER045 - Wheat
 EXPERIMENT      : PBWD1343 WH TEST2012WH TEST2011WH SUNI2011WH EFFECT OF ELEVATE
 TREATMENT  4    : D4


 CROP            : Wheat           CULTIVAR : PBW 343   (org)  ECOTYPE :INWH01
 STARTING DATE   : DEC  6 1913
 PLANTING DATE   : DEC  6 1913    PLANTS/m2 : 33.0     ROW SPACING :  20.cm
 WEATHER         : WRDM   1913
 SOIL            : IITR791201     TEXTURE : CL    - Dhanauri
 SOIL INITIAL C  : DEPTH:120cm EXTR. H2O:127.2mm  NO3: 46.2kg/ha  NH4:  5.3kg/ha
 WATER BALANCE   : AUTOMATIC IRRIGATION - REFILL PROFILE
 IRRIGATION      : AUTOMATIC - PLANTING -> MATURITY [ SOIL DEPTH:30.00m 50.%]
 NITROGEN BAL.   : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER    :      120 kg/ha IN     3 APPLICATIONS
 RESIDUE/MANURE  : INITIAL :   100 kg/ha ;        0 kg/ha IN     0 APPLICATIONS
 ENVIRONM. OPT.  : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= A  0.00
                   RAIN= A  0.00  CO2 = A   0.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT  : WATER   :Y  NITROGEN:Y  N-FIX:N  PHOSPH :N  PESTS  :N
                   PHOTO   :C  ET      :R  INFIL:S  HYDROL :R  SOM    :G
                   CO2     :D  NSWIT   :1  EVAP :R  SOIL   :2
 MANAGEMENT OPT  : PLANTING:R  IRRIG   :A  FERT :R  RESIDUE:N  HARVEST:M
                   WEATHER :M  TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS
```

SOIL DEPTH cm	LOWER LIMIT cm3/cm3	UPPER LIMIT	SAT SW cm3/cm3	EXTR SW	INIT SW cm3/cm3	ROOT DIST	BULK DENS g/cm3	pH	NO3 ugN/g	NH4 ugN/g	ORG C %
0- 5	0.121	0.224	0.414	0.103	0.136	1.00	1.50	7.80	2.60	0.30	0.20
5- 15	0.121	0.224	0.414	0.103	0.136	1.00	1.50	7.80	2.60	0.30	0.20
15- 30	0.121	0.224	0.414	0.103	0.136	1.00	1.50	7.80	2.60	0.30	0.20
30- 45	0.104	0.208	0.406	0.104	0.120	0.41	1.50	7.80	2.60	0.30	0.20
45- 60	0.104	0.208	0.406	0.104	0.120	0.41	1.50	7.80	2.60	0.30	0.20
60- 90	0.097	0.201	0.407	0.104	0.113	0.22	1.50	7.80	2.60	0.30	0.20
90-120	0.082	0.195	0.419	0.113	0.099	0.12	1.42	7.80	2.60	0.30	0.00

```
TOT-120  12.1  24.8  49.4  12.7  14.0  <--cm   -  kg/ha-->  46.2    5.3  27000
SOIL ALBEDO     : 0.13       EVAPORATION LIMIT : 6.00         MIN. FACTOR  : 1.00
RUNOFF CURVE # :73.00       DRAINAGE RATE     : 0.40         FERT. FACTOR : 1.00

 Wheat      CULTIVAR :IN0013-PBW 343   (org)    ECOTYPE :INWH01
 P1V    :  20.000  P1D    : 70.0000  P5     :  800.00
 G1     :  20.000  G2     :  45.000  G3     :   1.500  PHINT  :  95.000


*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES
```

YEARDOY	DOM	MON	DAP	GROWTH STAGE	BIOMASS kg/ha	LEAF AREA	LEAF NUMBER	CROP N kg/ha	CROP N %	STRESS H2O	STRESS N
1913341	6	Dec	0	7 Sowing	0	0.00	0.0	0	0.0	0.00	0.00
1913342	7	Dec	1	8 Germinate	0	0.00	0.0	0	0.0	0.00	0.00
1913345	10	Dec	7	9 Emergence	0	0.00	0.0	0	0.0	0.00	0.00
1914053	22	Feb	78	1 Term Spklt	1636	1.11	10.1	38	2.3	0.00	0.00
1914063	26	Feb	88	2 End Veg	2897	2.26	12.0	65	2.3	0.00	0.00
1914068	3	Mar	93	3 End Ear Gr	3834	1.66	12.0	65	1.7	0.00	0.00
1914075	10	Mar	100	4 Beg Gr Fil	5160	1.50	12.0	65	1.3	0.00	0.00
1914109	13	Apr	128	5 End Gr Fil	8987	0.00	12.0	76	0.8	0.00	0.25
1914109	13	Apr	128	6 Harvest	8987	0.00	12.0	76	0.8	0.00	0.00

```
*MAIN GROWTH AND DEVELOPMENT VARIABLES
```

@ VARIABLE	SIMULATED	MEASURED
Emergence (DAP)	7	-99
Anthesis (DAP)	95	-99
Maturity (DAP)	128	-99
Product wt (kg dm/ha;no loss)	3508	-99
Product unit weight (g dm)	0.040	-99.0
Product number (no/m2)	8769	-99
Product number (no/group)	29.0	-99.0
Product harvest index (ratio)	0.39	-99.00
Maximum leaf area index	2.2	-99.0
Final leaf number (one axis)	12.0	-99.0
Final shoot number (#/m2)	302	-99
Canopy (tops) wt (kg dm/ha)	8987	-99
Vegetative wt (kg dm/ha)	5479	0
Root wt (kg dm/ha)	394	-99
Assimilate wt (kg dm/ha)	10824	-99
Senesced wt (kg dm/ha)	339	-99
Reserves wt (kg dm/ha)	4113	-99
N uptake (kg/ha)	88.4	-99.0
N senesced (kg/ha)	7.9	-99.0
Above-ground N (kg/ha)	75.8	-99.0
Root N (kg/ha)	5.0	-99.0
Vegetative N (kg/ha)	8.6	-99.0
Product N (kg/ha)	67.1	-99.0
Product N harvest index (ratio)	0.89	-99.00
Product N (%)	1.8	-99.0
Vegetative N (%)	0.1	-99.0
Leaf+stem wt,anthesis (kg dm/ha)	4203	-99
Leaf+stem N,anthesis (kg/ha)	65.0	-99.0
Leaf N,anthesis (%)	4.3	-99.0

*ENVIRONMENTAL AND STRESS FACTORS

Development Phase	Environment: Average: Time Span days	Temp Max øC	Temp Min øC	Solar Rad MJ/m2	Photop [day] hr	Cumulative: Rain mm	Evapo Trans mm	Stress (0=Min, 1=Max Stress): Water Photo synth	Water Growth	Nitrogen Photo synth	Nitrogen Growth	Phosphorus Photo synth	Phosphorus Growth
Germinate - Term Spklt	74	18.0	7.4	12.1	11.40	195.3	96.2	0.000	0.000	0.000	0.000	-99.00	-99.00
Term Spklt - End Veg	10	24.2	11.9	16.0	12.22	0.0	33.0	0.000	0.000	0.000	0.000	-99.00	-99.00
End Veg - End Ear Gr	5	28.2	13.6	19.6	12.43	0.0	21.8	0.000	0.000	0.000	0.000	-99.00	-99.00
End Ear Gr - Beg Gr Fil	7	28.2	14.6	18.9	12.61	1.5	29.5	0.000	0.000	0.000	0.000	-99.00	-99.00
Beg Gr Fil - End Gr Fil	34	31.1	16.2	21.6	13.24	2.0	157.4	0.000	0.000	0.248	0.248	-99.00	-99.00
Germinate - End Gr Fil	131	22.9	10.6	15.5	12.04	198.8	338.0	0.000	0.000	0.064	0.064	-99.00	-99.00

*WATER PRODUCTIVITY

Growing season length: 128 days

Precipitation during growth season 198.8 mm[rain]
  Dry Matter Productivity 3.72 kg[DM]/m3[rain] = 37.2 kg[DM]/ha per mm[rain]
  Yield Productivity 1.42 kg[grain yield]/m3[rain] = 14.2 kg[yield]/ha per mm[rain]

Evapotranspiration during growth season 338.0 mm[ET]
  Dry Matter Productivity 2.87 kg[DM]/m3[ET] = 28.7 kg[DM]/ha per mm[ET]
  Yield Productivity 1.10 kg[grain yield]/m3[ET] = 11.0 kg[yield]/ha per mm[ET]

Transpiration during growth season 179.5 mm[EP]
  Dry Matter Productivity 5.40 kg[DM]/m3[EP] = 54.0 kg[DM]/ha per mm[EP]
  Yield Productivity 2.07 kg[grain yield]/m3[EP] = 20.7 kg[yield]/ha per mm[EP]

WHEAT YIELD : 3508 kg/ha [Dry weight]

***

Annexure –4

Micro climate observations

Table 1: CO_2 concentrations (ppm) before and after application of CO2 during 2011-12.

CO_2 Application (ppm) During 2011-12							
Dates	**CO_2 concentration at the time of application. (15:00 hr)**				**Residing CO_2 concentration after 15 minute of application: 15:15 hr**		
	T_0 (Amb.)	**T_1**	**T_2**	**T_3**	**T_1**	**T_2**	**T_3**
19/12/2011	290			761			587
21/12/2011	303		732	766		554	558
23/12/2011	313	765	760	732	540	565	569
26/12/2011	326			816			589
28/12/2011	320		770	762		576	610
30/12/2011	346	740	761	728	562	565	662
02/01/2012	297			744			591
04/01/2012	318		820	783		512	623
06/01/2012	301	746	755	745	542	571	562
09/01/2012	322			762			582
11/01/2012	277		817	791		575	675
13/01/2012	280	770	780	816	586	565	566
16/01/2012	305			744			628
18/01/2012	299		740	763		590	593
20/01/2012	277	790	820	744	561	555	545
23/01/2012	322			752			581
25/01/2012	297		765	765		566	582
27/01/2012	318	780	745	748	584	594	562
30/01/2012	304			762			545
01/02/2012	277		781	778		582	593
03/02/2012	290	768	741	842	558	564	584
06/02/2012	327			773			591
08/02/2012	285		762	765		563	586
10/02/2012	294	769	741	814	545	519	594
13/02/2012	327			735			572
15/02/2012	301		744	752		552	542
17/02/2012	357	755	723	781	572	595	513
20/02/2012	330			852			596
22/02/2012	284		763	748		582	586
24/02/2012	364	815	772	735	533	542	562
27/02/2012	294			896			562
29/02/2012	316		741	762		542	583
02/03/2012	290	734	785	843	515	540	598
Mean	**308**	**767**	**764**	**775**	**554**	**562**	**584**

Table: CO_2 concentrations (ppm) before and after application of CO2 during 2011-12

CO₂ Application (ppm) During 2011-12							
Dates	CO_2 concentration at the time of application. (15:00 hr)				Residing CO_2 concentration after 15 minute of application: 15:15 hr		
	T_0 (Amb.)	**T_1**	**T_2**	**T_3**	**T_1**	**T_2**	**T_3**
10/12/2012	349	745	754	720	576	541	512
12/12/2012	291		762	795		562	554
14/12/2012	342			772			645
17/12/2012	337	734	712	760	544	595	562
19/12/2012	334		776	765		576	545
21/12/2012	299			745			536
24/12/2012	345	791	742	744	574	591	584
26/12/2012	329		765	770		548	541
28/12/2012	307			840			562
31/12/2012	339	822	865	852	578	567	578
02/01/2013	320		849	787		514	563
04/01/2013	318			760			606
07/01/2013	325	865	790	741	512	608	530
09/01/2013	291		795	874		554	532
11/01/2013	294			762			652
14/01/2013	289	766	795	880	598	532	547
16/01/2013	311		714	830		653	589
18/01/2013	289			865			564
21/01/2013	329	745	742	845	576	552	562
23/01/2013	329		772	772		549	541
25/01/2013	349			813			572
28/01/2013	294	862	846	815	582	576	568
30/01/2013	311		751	780		541	591
01/02/2013	335			791			587
04/02/2013	323	789	743	797	571	544	534
06/02/2013	294		774	752		612	598
08/02/2013	319			770			571
11/02/2013	331	795	781	795	519	502	538
13/02/2013	322		735	740		612	591
15/02/2013	334			794			532
18/02/2013	337	745	814	728	606	592	524
20/02/2013	331		862	763		584	539
22/02/2013	332			895			604
Mean	**321**	**787**	**779**	**791**	**567**	**568**	**565**

Table: Leaf, Canopy and above canopy temperature (^{0}C) before and after of CO_2 application during 2011-12

Dates	Leaf temperature (^{0}C)							Canopy temperature (^{0}C)							Above Canopy temperature (^{0}C)						
	Before CO_2 application				After CO_2 application			Before CO_2 application				After CO_2 application			Before CO_2 application				After CO_2 application		
	T_0 (Amb.)	T_1	T_2	T_3	T_1	T_2	T_3	T_0 (Amb.)	T_1	T_2	T_3	T_1	T_2	T_3	T_0 (Amb.)	T_1	T_2	T_3	T_1	T_2	T_3
19/12/2011	14.5	14.7	14.5	14.5			14.5	18.0	18.2	18.2	18.2			18.3	17.9	17.9	17.9	17.8			18.0
21/12/2011	19.4	19.5	19.5	19.6		19.5	19.5	21.9	22.0	21.9	21.9		22.0	22.0	21.7	21.7	21.7	21.8		21.4	21.9
23/12/2011	15.5	15.6	15.4	15.5	15.2	15.4	15.4	18.4	18.8	18.3	18.3	18.4	18.4	18.4	18.5	18.1	18.1	18.1	18.2	18.2	18.8
26/12/2011	17.7	17.8	17.6	17.7			17.5	20.4	20.5	20.5	20.5			20.6	20.3	20.3	20.3	20.3			20.8
28/12/2011	19.9	20.1	19.9	20.0		20.0	19.9	23.4	23.9	23.6	23.6		23.7	23.7	23.3	23.3	23.3	23.2		23.5	23.8
30/12/2011	20.2	20.3	20.3	20.4	20.3	20.3	20.4	22.6	22.8	22.7	22.7	23.2	22.8	22.8	22.5	22.5	22.5	22.6	22.6	22.6	22.7
02/01/2012	18.3	18.4	18.2	18.3			18.2	20.9	21.1	21.1	21.1			21.3	20.9	20.9	20.9	20.9			21.0
04/01/2012	9.5	9.7	9.5	9.6		9.4	9.5	12.9	13.2	13.2	13.2		13.4	13.4	12.9	12.9	12.9	12.8		12.9	12.9
06/01/2012	16.0	16.1	16.1	16.2	16.1	16.2	16.2	18.4	18.6	18.5	18.5	18.6	18.6	18.6	18.3	18.3	18.3	18.4	18.5	18.2	18.5
09/01/2012	10.4	10.3	10.1	10.3			10.4	14.6	14.6	14.7	14.5			14.6	14.6	14.5	14.6	14.5			15.0
11/01/2012	14.6	14.8	13.9	13.8		14.1	13.9	18.3	18.3	18.1	18.0		18.2	18.2	18.3	18.3	18.0	17.9		18.1	18.1
13/01/2012	13.4	13.0	12.7	13.3	13.5	13.5	13.5	19.4	19.1	19.5	19.4	18.3	18.7	19.6	19.4	19.9	18.5	18.4	18.3	18.1	18.4
16/01/2012	14.0	14.0	14.1	13.9			14.1	18.3	18.1	18.2	18.4			18.5	18.3	18.2	18.2	17.3			18.4
18/01/2012	13.1	13.1	12.7	14.3		13.0	14.2	17.6	17.6	17.7	17.6		17.8	17.7	17.6	17.7	17.7	17.6		17.1	17.7
20/01/2012	12.6	12.8	12.7	12.4	13.0	13.1	12.8	17.6	17.8	17.3	17.0	17.5	17.4	17.4	17.1	17.4	17.2	17.0	17.5	17.2	17.1
23/01/2012	18.5	19.4	19.2	19.2			19.4	22.7	23.0	22.9	22.9			23.1	22.8	22.7	23.7	22.9			23.0
25/01/2012	17.7	17.4	17.7	17.8		17.8	17.9	20.7	21.1	20.6	21.0		20.8	21.1	20.8	21.2	20.8	21.2		20.9	21.4
27/01/2012	17.3	17.2	17.3	17.4	17.2	17.7	17.3	20.7	20.9	20.2	20.1	20.9	20.6	20.6	20.4	20.8	20.6	20.8	21.0	20.7	20.9
30/01/2012	15.9	15.6	16.0	16.0			16.2	18.9	19.3	18.8	19.2			19.4	19.4	19.4	19.0	19.4			19.8
01/02/2012	15.8	15.4	15.7	15.6		15.9	15.8	21.8	21.4	21.5	21.5		21.7	21.5	21.6	21.4	21.5	21.5		21.1	21.6
03/02/2012	19.3	19.4	19.3	19.1	19.1	19.8	19.2	23.8	24.0	23.8	23.7	24.3	23.9	23.8	24.7	24.1	24.1	23.5	24.3	24.2	24.6
06/02/2012	20.5	20.8	20.2	19.8			19.9	25.5	25.2	25.4	25.2			25.3	24.9	25.1	25.4	25.1			25.9
08/02/2012	13.4	13.4	13.2	13.3		13.4	13.3	23.6	23.4	23.4	23.1		23.5	23.2	23.2	23.5	23.1	23.8		22.5	23.2
10/02/2012	15.2	15.2	15.2	15.2	15.2	15.2	15.4	20.3	20.7	20.0	20.3	20.8	20.6	20.5	20.5	20.7	20.2	20.6	20.9	20.3	20.8
13/02/2012	17.1	16.8	17.2	17.3			17.2	21.4	21.6	21.0	21.4			21.8	20.9	20.9	19.8	19.4			20.4
15/02/2012	16.0	17.1	18.1	17.8		18.2	18.0	24.9	24.6	24.1	24.6		25.2	25.1	24.6	24.7	24.4	24.2		25.1	25.3
17/02/2012	15.2	15.8	16.0	16.3	15.3	15.9	16.4	23.8	23.8	23.2	23.4	23.9	24.3	23.5	23.8	23.9	24.2	23.4	23.9	24.0	23.5
20/02/2012	17.7	18.3	17.9	17.9			18.0	21.5	22.9	22.3	22.2			22.4	22.3	23.0	22.0	22.0			22.8
22/02/2012	21.7	22.3	21.9	21.9		22.0	21.8	27.9	27.7	27.9	27.8		28.0	28.2	27.9	27.6	27.6	27.6		27.9	27.7
24/02/2012	15.6	16.7	17.7	17.4	17.0	17.3	17.2	24.5	24.2	24.7	23.8	24.3	24.7	24.2	24.2	24.7	24.3	23.8	24.3	24.6	24.0
27/02/2012	17.2	17.1	17.1	17.2			17.1	23.2	23.8	23.3	23.3			23.5	23.7	23.9	23.3	23.1			23.8
29/02/2012	16.2	17.3	18.3	18.0		18.2	18.0	24.8	25.0	24.9	24.4		25.2	25.8	25.8	25.9	25.1	24.4		25.0	24.5
02/03/2012	20.6	21.2	20.8	20.8	21.1	20.5	20.7	26.0	26.6	26.3	26.7	26.7	26.8	26.8	25.8	26.5	25.5	25.6	26.5	26.5	26.5
Mean	**16.4**	**16.6**	**16.5**	**16.6**	**16.6**	**16.7**	**16.6**	**21.2**	**21.3**	**21.1**	**21.1**	**21.5**	**21.7**	**21.4**	**21.2**	**21.4**	**21.1**	**20.9**	**21.4**	**21.3**	**21.6**

Table: Leaf, Canopy and above canopy temperature (^0C) before and after of CO_2 application during 2012-13

Dates	Leaf temperature (^0C)							Canopy temperature (^0C)							Above Canopy temperature (^0C)						
	Before CO_2 application				After CO_2 application			Before CO_2 application				After CO_2 application			Before CO_2 application				After CO_2 application		
	T_0 (Amb.)	T_1	T_2	T_3	T_1	T_2	T_3	T_0 (Amb.)	T_1	T_2	T_3	T_1	T_2	T_3	T_0 (Amb.)	T_1	T_2	T_3	T_1	T_2	T_3
10/12/2012	20.0	20.4	20.2	20.5			20.6	25.5	25.3	25.4	25.3			26.5	25.3	25.6	25.6	25.8			25.8
12/12/2012	16.4	16.9	16.9	17.1		17.4	17.1	20.8	20.5	21.3	21.3		21.8	21.5	20.6	20.8	20.8	20.7		20.9	20.7
14/12/2012	15.2	15.1	15.4	15.4	15.8	15.1	15.0	17.7	17.2	17.4	17.3	17.8	17.5	17.5	17.6	18.0	17.9	17.9	18.4	18.0	18.0
17/12/2012	16.2	16.3	16.3	16.5			16.6	18.5	18.3	18.4	18.8			19.1	18.4	18.6	18.6	18.6			18.7
19/12/2012	16.4	16.8	16.6	16.9		17.1	17.0	19.9	20.3	20.2	20.3		20.3	20.5	19.7	20.0	20.0	19.8		20.0	19.9
21/12/2012	9.7	9.1	9.2	9.4	9.4	9.7	9.5	11.8	12.1	12.1	12.1	12.9	12.6	12.3	11.3	11.8	11.8	11.8	12.0	12.5	12.0
24/12/2012	18.2	18.1	18.1	18.3			18.5	23.1	23.4	23.4	23.3			23.3	22.8	22.5	22.2	22.4			22.6
26/12/2012	8.8	8.5	8.5	8.8		9.1	9.1	12.6	12.9	12.9	12.9		13.7	13.2	12.5	12.7	12.5	12.6		12.9	12.8
28/12/2012	15.4	15.4	15.6	15.5	15.9	15.9	15.8	19.9	19.4	20.1	20.5	20.8	20.7	20.8	19.5	20.1	20.2	20.1	20.8	20.3	20.2
31/12/2012	9.1	9.2	9.1	9.4			9.4	13.5	13.7	13.7	13.7			14.1	13.4	13.3	13.3	13.3			13.4
02/01/2013	9.4	9.1	9.6	9.4		10.0	9.7	13.2	13.5	13.5	13.5		14.2	13.8	13.1	13.3	13.1	13.2		13.1	13.3
04/01/2013	8.2	8.2	8.4	8.3	8.7	8.7	8.6	12.7	13.2	13.3	13.3	13.8	13.7	13.6	12.3	12.9	13.0	12.9	13.5	13.1	13.0
07/01/2013	7.4	7.8	7.5	7.8			7.9	10.0	10.1	10.4	9.9			10.5	9.7	9.8	9.7	9.2			9.5
09/01/2013	9.3	9.7	9.8	9.7		10.1	10.0	11.9	12.3	12.3	11.8		12.6	12.1	11.3	11.7	11.5	11.1		12.0	11.6
11/01/2013	11.4	11.4	11.6	11.5	11.8	12.1	11.7	16.6	16.4	16.7	16.7	17.1	16.9	16.9	15.9	16.2	16.2	16.2	16.8	16.7	16.3
14/01/2013	18.4	18.1	18.1	18.2			18.5	20.2	20.3	20.3	20.6			20.8	20.1	20.3	20.2	20.3			20.8
16/01/2013	19.8	19.6	19.6	19.7		20.1	20.1	21.8	21.9	21.9	21.2		22.1	22.5	21.7	22.0	21.8	22.2		22.2	22.3
18/01/2013	13.7	13.3	13.2	13.3	14.0	13.8	13.7	15.5	15.5	15.6	15.6	16.3	15.9	16.1	15.4	15.6	15.5	15.6	15.9	15.8	15.8
21/01/2013	17.5	17.4	17.3	17.4			17.7	19.5	19.2	19.1	19.3			20.1	19.4	19.6	19.5	19.6			20.0
23/01/2013	9.4	9.2	9.2	9.3		9.9	9.7	11.4	11.1	11.5	11.8		11.6	12.1	11.3	11.6	11.4	11.8		11.8	11.9
25/01/2013	17.4	17.1	17.1	17.4	17.8	17.5	17.5	19.5	19.4	19.4	19.7	19.8	19.9	19.8	19.2	19.4	19.3	19.4	19.5	19.4	19.7
28/01/2013	15.7	15.6	15.5	15.6			15.9	17.7	17.2	17.8	17.5			18.2	17.6	17.8	17.7	17.8			18.2
30/01/2013	17.2	17.2	17.0	17.3		17.9	17.4	19.2	19.3	19.3	19.6		19.6	19.8	19.1	19.3	19.2	19.3		19.8	19.5
01/02/2014	19.5	19.2	19.2	19.5	19.9	19.6	19.6	21.6	21.5	21.5	21.8	21.7	21.7	21.9	21.3	21.5	21.4	21.5	21.6	21.9	21.8
04/02/2013	14.3	14.0	14.2	14.3			14.1	16.2	16.3	16.3	16.6			16.6	16.1	16.3	16.2	16.3			16.4
06/02/2013	16.9	16.7	16.8	16.8		17.1	17.0	18.8	18.5	18.6	18.5		19.1	19.3	18.7	18.9	18.8	18.9		19.7	19.1
08/02/2013	18.9	18.6	18.7	18.9	19.1	19.7	19.0	20.8	20.4	20.9	21.2	21.4	21.6	21.5	20.7	20.9	20.8	20.9	21.0	20.9	21.2
11/02/2013	20.4	20.1	20.2	20.4			20.3	22.4	22.5	22.5	22.5			22.9	22.3	22.5	22.4	22.5			22.6
13/02/2013	21.1	20.9	20.7	21.0		21.3	21.2	23.0	23.1	23.1	23.4		23.3	23.5	22.9	23.1	23.0	23.1		23.6	23.3
15/02/2013	16.2	15.9	16.0	16.0	16.5	16.8	16.2	18.0	18.1	18.1	18.2	18.7	18.3	18.7	17.9	18.1	18.0	18.1	18.2	18.6	18.4
18/02/2013	18.5	18.3	18.1	18.6			18.5	20.6	20.7	20.7	20.8			20.9	20.5	20.7	20.6	20.7			20.8
20/02/2013	20.4	20.4	20.4	20.7		20.9	20.8	22.6	22.1	22.7	23.0		23.3	23.1	22.5	22.7	22.6	22.7		23.0	22.9
22/02/2013	21.3	21.1	21.0	21.3	21.5	21.4	21.4	23.2	23.3	23.3	23.6	23.9	23.7	23.7	23.1	23.3	23.2	23.3	23.6	23.6	23.4
Mean	**15.4**	**15.3**	**15.3**	**15.5**	**15.5**	**15.5**	**15.6**	**18.2**	**18.1**	**18.3**	**18.3**	**18.6**	**18.4**	**18.7**	**18.0**	**18.2**	**18.1**	**18.2**	**18.3**	**18.2**	**18.4**

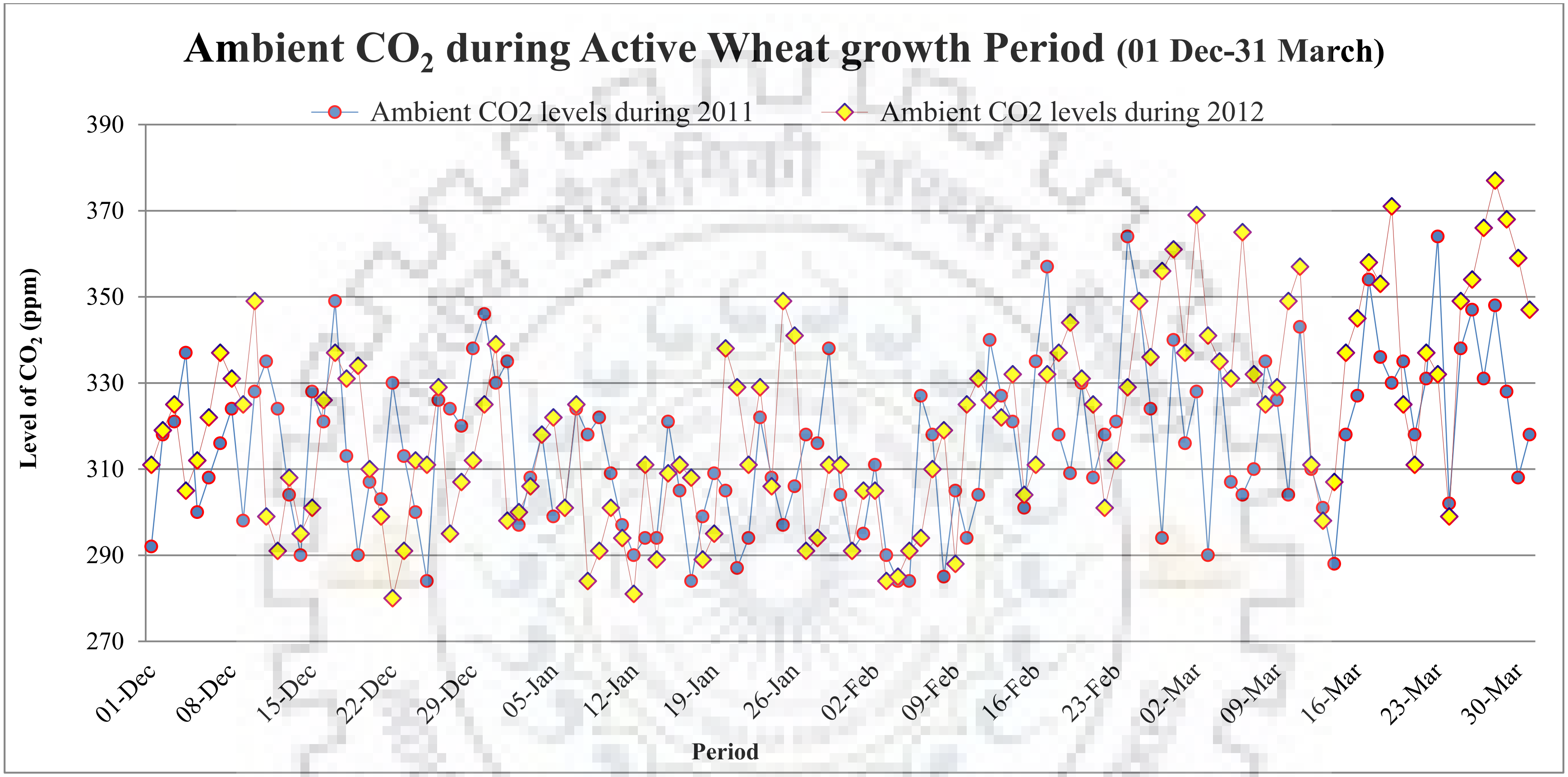


Figure: Ambient CO_2 condition during Wheat growth Period

Annexure –5

Brief history of variety used

A brief account of the variety used in experiment and its salient features are given below. (online access on 21.07.2015 http://smis.dacnet.nic.in/(S(2vvxorlkdand0ilqye4b53ot))/report/ssrsVarietydetail.aspx?varietycd=A0104012)

SALIENT FEATURES OF VARIETY

21/07/2015

Group Name	**CEREALS**	Notification Number	**1(E)**
Crop Name	**WHEAT (GEHON)**	Notification Date	**01/01/1996**
Variety Name	**PBW-343**	State /Central Variety	PUNJAB
Year of Release	1995		

1	Institution Responsible for developing Breeder Seed	WHEAT SECTION, DEPARTEMENT OF PLANT BREEDING PAU, LUDHIANA.
2	Parentage	ND/VG9144/KAL/BB/3/YCO/"S"/4/VEE/5/"S"/
3	Resemblence to Variety	
4	Adaptation and recommended ecology	RECOMMENDED FOR RELEASE AND CULTIVATION IN WHOLE OF NORTH WESTERN PLAINS ZONE FOR TIMELY SOWN IRRIGATED CONDITIONS.
5	Maturity (in days)	MEDIUM. SEED TO SEED 142 to 142 Days
6	Agronomic Features	IT IS HIGHLY RESISTANT TO LODGING AND HIGHLY RESPONSIVE TO FERTILIZATION WITH SUITABILITY FOR EARLY AND NORMAL SOWN CONDITIONS.
7	Seed Rate (Kg/Ha)	100
8	Specific Morphological Characteristics	THE EAR COLOUR AT MATURITY IS WHITE SHINING.THE EAR HEADS ARE DENSE AND TAPERING IN SHAPE.; INTERMEDIATE PEDUNOLE AND STRAW IS SHINING AT MATURITY.
9	General Morphological Characteristics	PLANT HEIGHT : 96 CM
10	Reaction to Stress	NONE.
11	Reaction to Major Diseases	IT IS HIGHLY RESISTANT TO BOTH YELLOW AND BROWN RUSTS.IT HAS RECORDED LOWEST INFECTION OF KERNEL BUNT EVEN UNDER ARTIFICIALLY INOCULATED CONDITIONS.
12	Reaction to Major Pests	NONE.
13	Average Yield (Kg/Ha)	4510 to 4590 Kg/Ha
14	Spacing (in Cms)	ROW TO ROW 25-30 Cms
15	Fertiliser Dosage (Kg/Ha)	N 80-150 , P 40-60 , K 40
16	Recommended States	