Dry biomass partitioning of growth and development in wheat (*Triticum aestivum* L.) crop using CERES-wheat in different agro climatic zones of India

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The CERES-wheat crop growth simulation model has been calibrated and evaluated for two wheat cultivars (PBW 343 and PBW 542) for three sowing dates (30 October, 15 November and 30 November) during 2008–09 and 2009–10 to study partitioning of leaf, stem and grains at Ludhiana, Punjab, India. The experimental data and simulated model data were analysed on partitioning of leaf, stem and grains, and validated. It was found that the model closely simulated the field data from phenological events and biomass. Simulated biological and grain yield was in accordance with-field experiment crop yield within the acceptable range. The correlation coefficient between field-experiment and simulated yield data and biomass data varied significantly from 0.81 and 0.96. The model showed overestimation from field-experimental yield for both cultivars. The cultivar PBW 343 gave higher yield than cultivar PBW 542 on 15 November during both years. The model performance was evaluated and it was found that CERES-wheat model could predict growth parameters like days to anthesis and maturity, biomass and yield with reasonably good accuracy (error less than 8%) and also correlation coefficient between field-experimental and simulated yield data and biomass data varied from 0.94 and 0.95. The results showed that the correlation coefficient between simulated and districts yield varied from 0.41 to 0.78 and also significantly at all six selected districts. The results may be used to improve and evaluate the current practices of crop management at different growth stages of the crop to achieve better production potential.

Keywords: Biomass partitioning, genetic coefficient, phenology stages, soil parameters.

INFORMATION necessary for agricultural decision-making at all levels is increasing rapidly due to increased demands for agricultural products and increased pressures on land, water and other natural resources. Wheat (*Triticum aestivum* L.) is one of the important staple foods in India and is grown under diverse sets of agro-climatic conditions during winter (*rabi*) season. It is a C3 plant and as such thrives in cool environments. Wheat requires about 10°C at the time of sowing, 15°C for plant growth and 20°–25°C at physiological maturity of crop. The temperature of plant organs in the field may differ from air temperature by several degrees. This difference increases with a greater rate of transpiration[1]. Temperature has a differential effect on each of the phases[2,3]. During recent years due to increased climatic variabilities and weather abnormalities, particularly extreme rise in temperature during the wheat growing season affects the productivity per hectare in India[4]. Temperature affects the photosynthesis and dry matter accumulation more during seedling growth or near maturity. During the grain filling stage, the reverse mobilization of assimilates takes place. The daily plant growth is computed by converting daily intercepted photosynthetically active radiation (PAR) into plant dry matter using a crop-specific radiation use efficiency parameter. Light interception is computed as a function of leaf area index, plant population and row spacing. Each day the amount of new dry matter available for growth may also be modified by limiting water or nitrogen stress, temperature and also atmospheric CO_2 concentration. Above-ground biomass has priority for carbohydrates, and at the end of each day, carbohydrates not used for above-ground biomass are allocated to the roots. However, the roots must receive a specified stage-dependent minimum of the daily carbohydrates available for growth. Leaf area is converted into new leaf weight using empirical functions[5]. Wheat needs low temperature for the kernel to form during booting stage. Wheat has

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*For correspondence. (e-mail: pksingh66@gmail.com) not encountered increased temperature at booting and anthesis stages; but the temperature was significantly higher than normal during grain-filling period, thus adversely affecting the grain-filling process and diversion of biomass to undesirable plant parts. The present study was, therefore, undertaken to observe whether dry matter partitioning would be the appropriate trait linked to yield in wheat genotypes under aberrant temperature variations. Dry matter partitioning is the end result of the flow of assimilates from source organs via a transport path to the sink organs. Dry matter partitioning among the sinks of a plant is primarily regulated by the sinks themselves. The effect of source strength on dry matter partitioning is often not a direct one, but indirect via the formation of sink organs. Although the translocation rate of assimilates may depend on the transport path, the latter is only of minor importance for the regulation of dry matter partitioning at the whole plant level. Partitioning of photosynthates from source to sink was reported to be affected by relative sink size, source and sink distance, growth stages, inter-sink competition and position of the sink[6,7]. The partitioning of biomass into leaves, stem, roots and reproductive organs shows that all the plant organs are not equally sensitive to environment stress[8,9–12]. During the past decade the ability of the CERES-wheat model to realistically simulate the observed wheat yields in the region has been established using the daily weather data of six stations, viz. Ludhiana (Punjab), Hisar (Haryana), Jaipur (Rajasthan), Indore (Madhya Pradesh), Faizabad and Varanasi (Uttar Pradesh). Figure 1 shows geographical location of these stations. Table 1 presents the soil characteristics of selected sites, weather data and wheat crop data with genetic coefficient of cultivars (PBW 343, PBW 542, WH 1150, HD 2733 and LOK1). The responses of biomass partitioning with crop growth and yield in the region due to variability of weather parameters have been examined.

Materials and methodology

Punjab Agricultural University (PAU), Ludhiana is situated in central plain zone of Punjab (30°56′N, 75°48′E at an altitude of 247 m amsl). The *rabi* season mean maximum temperature was found to be 24.5°C and the mean minimum temperature was 10.7°C. The mean sunshine hours received during the *rabi* season was 7.3 h. Rainfall was normal (107 mm) during the crop season. The field experiment on wheat during *rabi* 2008–09 and 2009–10 with two cultivars, viz. PBW 343 and PBW 542 under three sowing dates, viz. 30 October, 15 November and 30 November, was conducted at PAU. CCSHAU is situated in the Trans-Gangetic Plain region of Hisar district (29°15′N, 75°72′E at an altitude of 215 m amsl). The experiment was conducted here on wheat crop during *rabi* 2014–15 with cultivar WH 1150 under three sowing dates, viz. 20 November, 5 December and 20 December. Study of the biomass partitioning of different locations, viz. Ludhiana (2008–09 and 2009–10), Hisar (2009–10), Jaipur (2008–09), Indore (2005–06), Faizabad (2005–06) and Varanasi (2005–06) was conducted in differing climatogies. The point data on daily weather (maximum and minimum temperature, rainfall and sunshine hours) and the historical actual wheat crop data were collected for different locations (Ludhiana, Hisar, Jaipur, Indore, Faizabad and Varanasi) for the period 1990–2014 under the Forecasting Agricultural output using Space Agrometerology and Land (FASAL) based observations project, Agromet Service Cell (ASC), India Meteorological Department (IMD), New Delhi (Table 1).

Model description and its validation

Crop models which share a common input and output data format have been developed and embedded in a software package called Decision Support System for Agrotechnology Transfer (DSSAT). This package is a shell that allows the user to organize and manipulate crop, soil and weather data, and to run crop models in various ways and analyse their outputs[13–15].

CERES is a genetic, physiological, process oriented legume crop growth model. The major components of CERES-wheat model are the vegetative and reproductive development, carbon balance, water balance and nitrogen balance modules which relate the flow of mass and information between different modules. The basic structure of the model, including underlying equations, is

Figure 1. Location of selected stations in the different states (Punjab, Haryana, Rajasthan, Madhya Pradesh and Uttar Pradesh) of India considered in this study.

Table 1. Soil characteristics, weather data and district wise wheat yield and cultivars of different locations used

Station	Periods weather/crop	Soil depth (cm)	Lower limit/upper limit (mm)	Cultivars
Ludhiana	1990–2014	160	120/220	PBW 343 and PBW 542
Hisar	1990–2014	170	140/260	WH 1150
Jaipur	1990–2014	140	130/280	HD 2733
Indore	1990–2014	150	152/260	LOK-1
Faizabad	1990–2014	150	120/240	PBW 343
Varanasi	1990–2014	150	160/280	PBW 343

Source: Singh *et al.*[35,38].

explained in the literature[16–18]. The model accounts for vegetative and reproductive development, photosynthesis, respiration, partitioning, e.g. growth of leaves, stems, roots, shells and seed, transpiration, root water uptake, soil evaporation, soil water flow, infiltration and drainage[16,19].

Model input data

The input data required to run CERES-wheat model include the daily weather data, soil albedo, soil drainage constant, field capacity, wilting point, initial soil moisture in different layers, maximum root depth, crop genetic coefficients and management practices (plant population, plant row spacing and nitrogen application)[15]. Other input files include chemical and physical description of the soil profile with separate information for each horizon, initial organic matter in the soil at the beginning of the experiment, initial soil water content, nitrogen concentration and pH for each layer of the soil profile, date and amount of irrigation required for irrigation management, date, amount and type of fertilizer required for fertilizer management, planting date and depth, row and plant spacing, and other information for crop management, cultivars and crop-specific characteristics and genetic coefficients.

Weather module

The main function of the weather module is to read or generate daily weather data. It reads in daily weather values (maximum and minimum air temperature, solar radiation and precipitation) from the daily weather file. Hourly weather values are computed for use by the modules which require them. Solar radiation is derived from sunshine hours data Angstrom method[20]. This module generates daily weather data using the WGEN[21,22] or SIMMETEO[23,24] weather generators.

Soil module

The soil in the land unit is represented as a one-dimensional profile; it is homogenous horizontally and consists of a number of vertical layers. The soil module integrates information from four sub-modules: soil water, soil temperature, soil carbon and nitrogen, and soil dynamics. The physical and chemical parameters of the soil are required. The soil albedo, soil water drainage constant, field capacity, wilting point, layer-wise information on initial soil moisture, organic carbon, pH, and sand, silt and clay information were collected from the six selected stations. The terms lower limit and upper limit correspond to the permanent wilting point and field capacity respectively[25]. The total extractable soil water is a function of soil physical characteristics as well as rooting depth.

Crop data/cultivar module

Cultivars of wheat crop are popular varieties grown by the farmers of selected six regions. Water and nitrogen management parameters considered in the model are according to agronomical recommendations widely accepted/practised in these agroclimatic zones and field experiments conducted by Agro-Met-Field Units (AMFUs) under the FASAL project of IMD for wheat crop and cultivars.

Genetic coefficient module

Crop genetic input data which explain how the life cycle of a wheat cultivar responds to its environment have been developed for cultivars PBW 343 and PBW 542, which are one of the commonly grown varieties in Ludhiana[26] (Table 1). The coefficients were derived iteratively using Hunt's method[27]. The coefficients derived can be satisfactorily utilized for evaluation of growth performances of the crop under growth management situations in Punjab and Haryana. Minimum crop datasets used for the calculation of phenology and growth coefficients included dates of emergence, flowering, silking, beginning of grain-filling, maturity and grain yield, above ground biomass, grain number per cob and kennel weight. The genetic coefficients already developed for different wheat cultivars were used[26,28] (Table 1).

Results and discussion

The CERES-wheat crop growth simulation model was calibrated and evaluated for different cultivars of wheat-growing areas in selected six stations. The validation of simulated data and field-experimental data were used on leaf area index (LAI), leaf weight roots, stem weight, ear weight, total dry weight, biomass and yield data, and with both cultivars PBW 343 and PBW 542 for the period 2008–09 and 2009–10, with different sowing dates at Ludhiana. The validated simulated data and field-experimental data were also used on biomass and yield data with cultivar (WH 1150) for the period 2014–15, with different sowing dates at Hisar.

The model performance was assessed by running the model with independent crop dataset for all three sowing dates and two cultivars (PBW 343 and PBW 542) at Ludhiana. The emergence of simulated days was underestimated from the field-experimental data during 2008–09, but overestimated during 2009–10 for both cultivars and the data was computed. The November sown wheat crops took more days to complete their life cycle compared to December-sown crops. The CRI stage day of the field data was underestimated from simulated CRI stage day in cultivar PBW 343 but was overestimated from simulated CRI stage day in cultivar PBW 542 under 30 October, 15 November and 30 November dates of sowing and was computed in the year 2008–09. The CRI stage of experiment day was overestimated from simulated days of CRI stages for both the cultivars during 2009–10. The simulated anthesis day was underestimated from field-experimental anthesis day in both cultivars and years and was computed days of anthesis under 30 October, 15 November and 30 November dates of sowing. The duration of anthesis and maturity days decreased in both cultivars due to increase in temperature in 2009–10.

Leaf area index at Ludhiana

The CERES-wheat model was calibrated for LAI for comparing the field-experimental LAI data and simulated LAI data at Ludhiana. The data on periodic LAI for both cultivars of wheat PBW 343 and PBW 542 under three dates of sowing are presented in Figure 2 *a* and *b*. In general, the cultivar PBW 343 attained higher LAI values compared to PBW 542 for all three dates of sowing and also simulated LAI was overestimated. Early-sown wheat crop attained higher value of LAI compared to late-sown crop (Figure 2 *a* and *b*). The daily plant growth was computed by converting daily intercepted photosynthetically active radiation (PAR) into plant dry matter using a crop-specific radiation use efficiency parameter. Light interception was computed as a function of LAI, plant population and row spacing. The amount of new dry matter available for each day growth can also be modified by limiting water or nitrogen stress, temperature and is sensitive to atmospheric CO_2 concentration. Roots must receive, however, a specified stage-dependent minimum of daily carbohydrates available for growth.

Dry matter accumulation and its partitioning at Ludhiana

The simulated and field-experimental partitioning of weight (leaf, stem, ear head weight and total dry weight) data was used for both the cultivars for three different sowing dates of 2008–09 and 2009–10. The simulated and field-experimental partitioning factors (leaf, stem and grain fractions of the total dry matter of plant) were used for various components of wheat crop from sowing to harvesting during the crop-growing years. The data on periodic dry matter accumulation and its partitioning into various plant parts, i.e. leaf, stem, ear head and total dry weight are shown for the years 2008–09 and 2009–10 in Figures 3 *a*–6 *d*. In general, more dry matter had accumulated in cultivar PBW 343 compared to cultivar PBW 542 for all three dates of sowing and simulated its partitioning into various wheat plant parts, i.e. leaf, stem, ear head and total dry weight. The simulated partitioning weight was overestimated and underestimated for some days from field-experimental weight of sowing to harvesting. Early sown wheat crops attained higher dry matter accumulation compared to late sown crops. The weight of root was increased from sowing to tillering stage up to 30 days than decreased due to leaf weight. Both the field-experimental and simulated leaf weight was increased up to 120 days and decreased up to harvesting of leaf weight in both cultivars for both the years (30 October and 15 November). The simulated leaf weight was decreased from field-experimental leaf weight from sowing to harvesting in the third sowing date (30 November). The result showed that the field-experimental leaf weight was underestimated from simulated leaf weight in both years and cultivars[11,12,29–33] (Figure 3 *a*–*d*).

The field-experimental stem weight was overestimated from simulated stem weight for both cultivars and both years in 30 October, 15 November and 30 November sowings (Figure 4 *a*–*d*). The field-experimental data ear heads increased from 90 to 135 days. But the first and second sowing dates were overestimated for both the cultivars in field-experiment and simulated ear head weight while the third sowing was underestimated from field experiment data of ear heads (Figure 5 *a*–*d*). The total dry weight increased from 30 to 135 days for the first and second sowing date, but increased from 30 to 120 days in the third sowing date (both simulated and field-experiment dry weight for both cultivars). The simulated dry weight was underestimated for the third date of sowing and both first and second sowing dates were overestimated (Figure 6 *a*–*d*). In general, more dry matter was

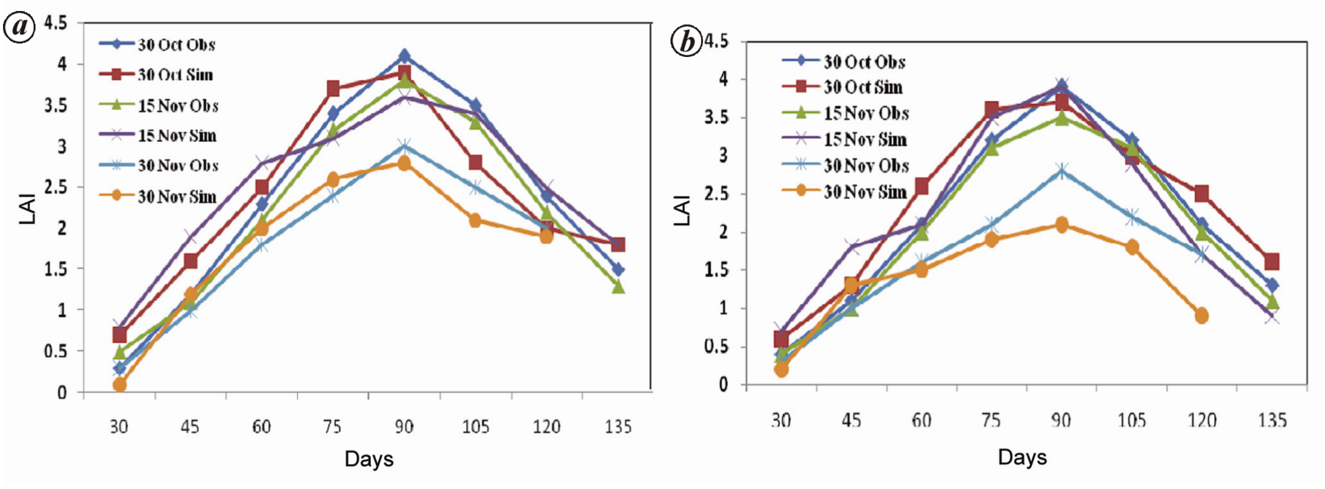

Figure 2. Validation between field-experimental and simulated LAI of two cultivars (***a***) PBW 343 and (***b***) PBW 542 at Ludhiana (2008–09).

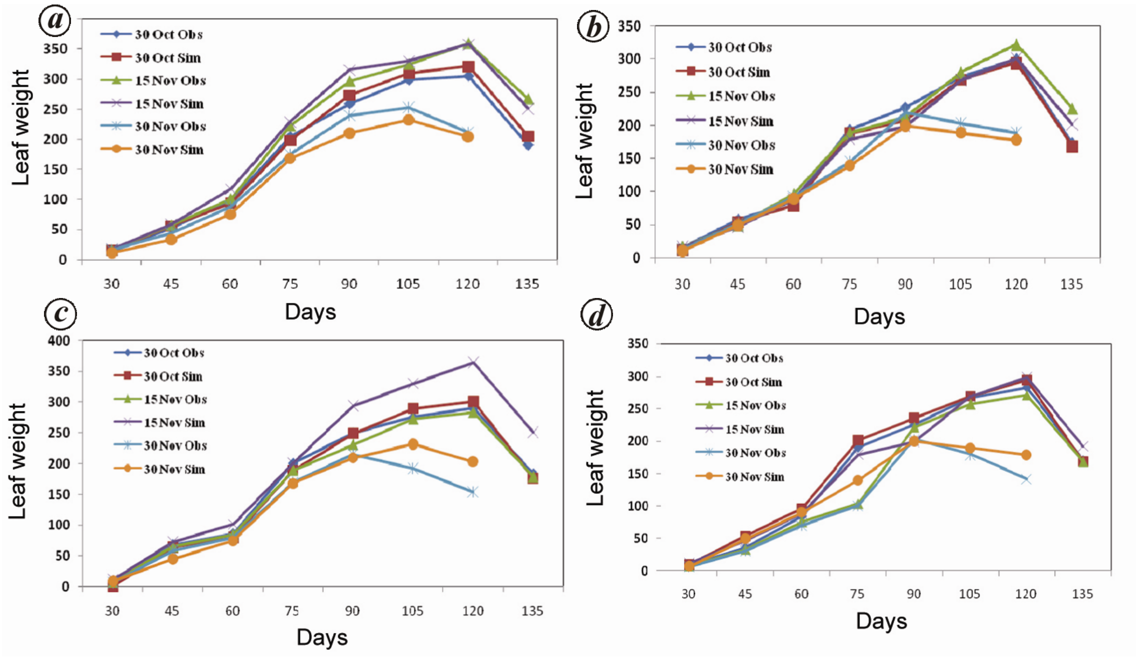

Figure 3. Validation between field-experimental and simulated leaf weight of cultivars (***a***) PBW 343; (***b***) PBW 542 (2008–09) and (***c***) PBW 343; (***d***) PBW 542 (2009–10) at Ludhiana.

accumulated in cultivar PBW 343 compared to cultivar PBW 542 for all dates of sowing. Early sown wheat crop attained higher dry matter accumulation compared to late sowings[11,12,29–33]. Overall, the field experiment data were overestimated from simulated data for both the cultivars. The maximum temperature was below normal during November (1°–3°C), near normal during December, below normal during January (4°–7°C) and again near normal during February months. At the start of March, the maximum temperature was above normal by 1°–3°C during the first fortnight, 6°–7°C during the second fortnight and 5°–6°C during the first fortnight of April (Figure 7). The sunshine hours were invariably below normal up to mid February by nearly 0.5–5.9 h in both years. Later, they became near-normal and were above normal during March.

The model was also used to simulate wheat crop for the partitioning and coefficient factors (root, leaf, stem and grain) for comparing both the cultivars for field-experimental data and simulated data during both the years at Ludhiana. It has been simulated for the weight of root, leaf, stem and grain that the root and leaf weight increased up to 67 days then decreased up to harvesting[11,12,29–33] (Figure 8 *a*–*e*). The partitioning of dry matter to leaves was higher than root and stem, except for roots at 20 day after sowing (DAS). After the decrease in root

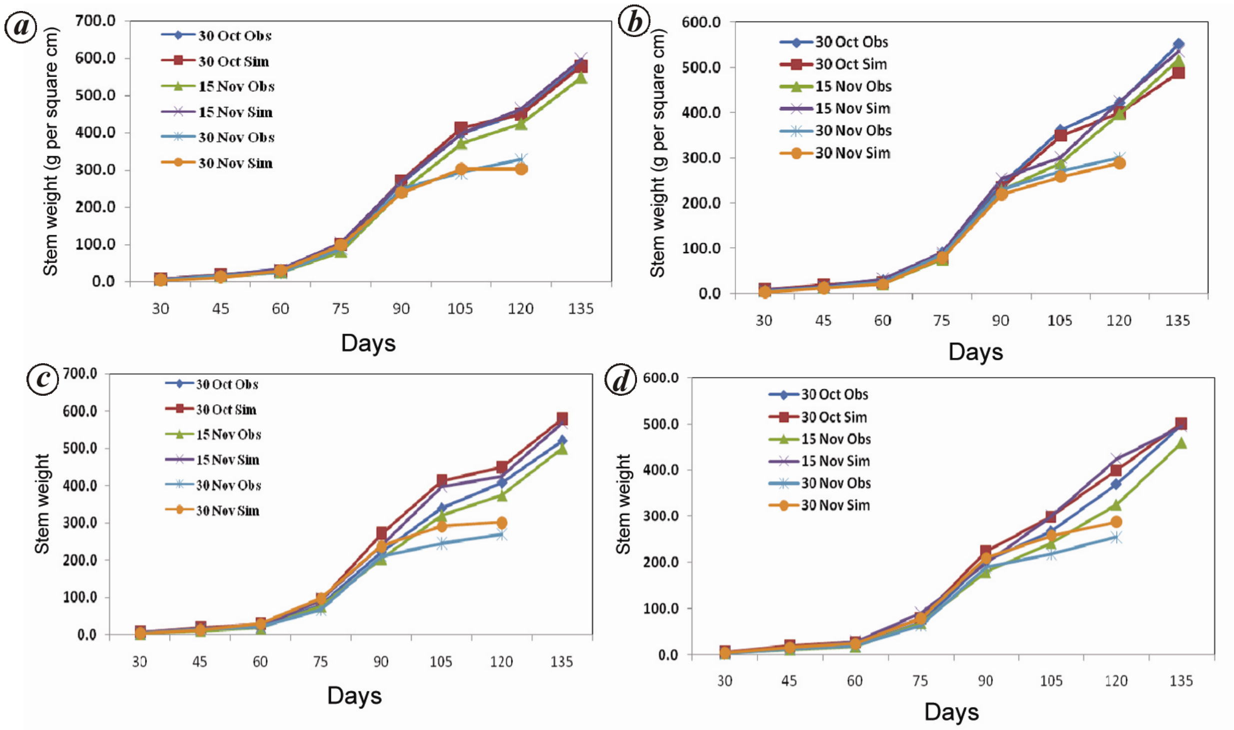

Figure 4. Validation between field-experimental and simulated stem weight of cultivars (***a***) PBW 343; (***b***) PBW 542 during (2008–09) and (***c***) PBW 343; (***d***) PBW 542 (2009–10) at Ludhiana.

and increased of leaf weight, stem weight and grain weight increased up to harvesting for both the cultivars (Figure 8 *a–e*). The leaf weight increased up to 69 days; and the stem weight increased from 80 to 120 days, and then it decreased. The weight of grain increased from 95 days to harvesting. Partitioning of the photosynthesis assimilates to grain was higher for 2008–09, which led to higher biomass production and hence better crop yield in simulation compared to 2009–10 (refs 11, 12, 29–33). Overall the weight of root and leaf first increased and then decreased up to harvesting, but after vegetative stages over reproductive stages increased up to harvesting in both the years (2008–09 and 2009–10). This proved beneficial for the early vegetative stage, as it led to prolonged tillering stage and after 105 days, the stem and grain started increasing up to harvesting.

The coefficient of root and shoots (leaf, stem and grain) decreased up to 30 days and increased the root and shoot coefficients up to harvesting as shown in Figure 8 *a–e* (refs 11, 12, 29–33). After the decrease of the root and leaf coefficients, the stem and grain coefficients started increasing up to harvesting of the crop for both the years due to the partitioning of the photosynthates assimilation toward grain. It was higher in the cultivar PBW 343 in 2008–09, which led to higher biomass production and hence better crop yield in simulation than during 2009–10 (Figure 8 *a–e*). The maximum dry weights of leaves and stems were observed at flowering stages and thereafter declined till harvesting, however, the dry weights of stem, root and grain increased consistently up to harvesting[11,12,29–33]. The contribution of leaves to total biomass reduced after flowering, but percentage of contributions (36 and was computed) of stem increased up to pod-filling stages and declined thereafter. The strong sources (leaves and stems) may also help to produce higher grain yield due to their large capacity to mobilize more pre-anthesis assimilation to grain[11,12,29–33]. The daily growth rate was modified by temperature and availability of assimilates. If the daily pool of carbon is insufficient to allow growth at the potential rate, a fraction of carbon can be remobilized from the vegetative to reproductive sinks each day. Kernels are allowed to grow until physiological maturity was reached. If the plant runs out of resources, growth was terminated prior to physiological maturity. Likewise, if the grain growth rate was reduced below a threshold value for several days, growth was also terminated[29,34,35].

Yield attributes at Ludhiana

The CERES-wheat model was evaluated and validated for simulating wheat crop (yield and biomass) by comparing field-experimental data and simulated data. The field-experimental biomass weight were underestimated from simulated biomass weight of first and third sowing dates, but was overestimated from simulated biomass weight for cultivar PBW 343 of the second sowing during both the

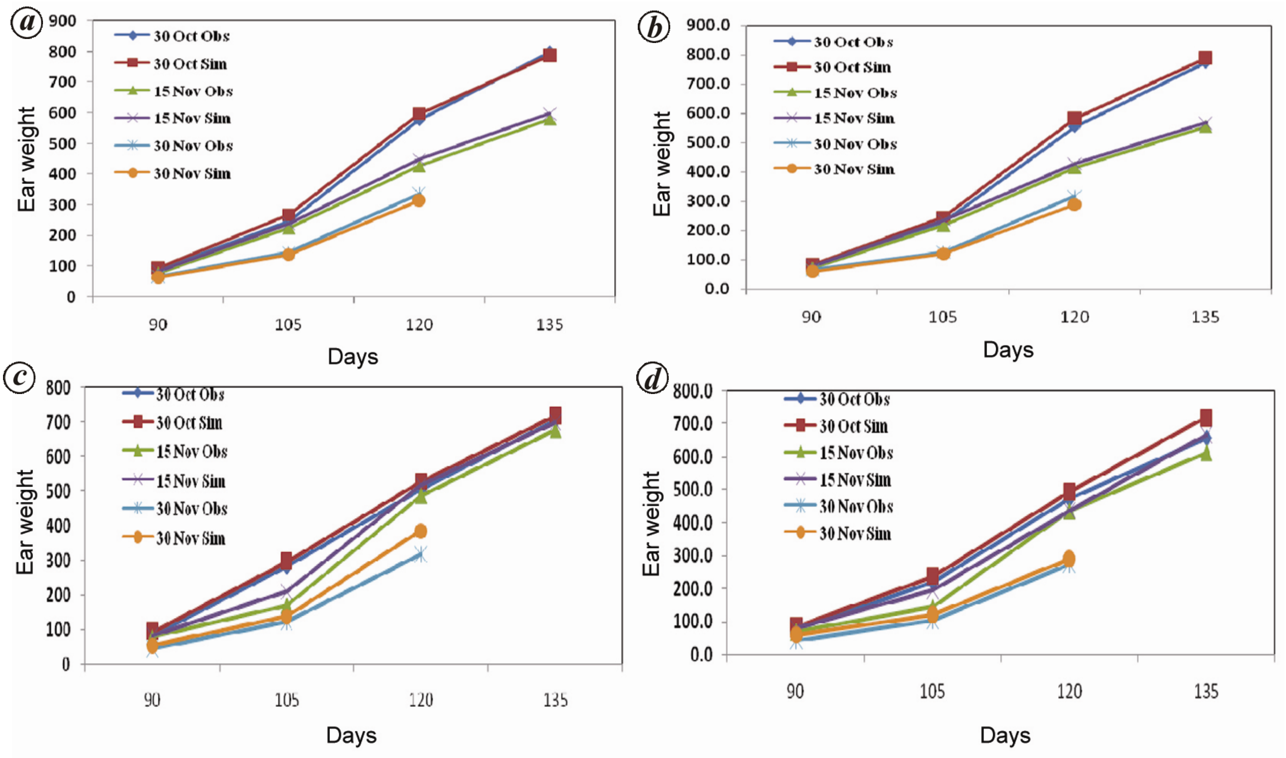

Figure 5. Validation between field-experimental and simulated ear head weight of cultivars (***a***) PBW 343; (***b***) PBW 542 during (2008–09) and (***c***) PBW 343; (***d***) PBW 542 (2009–10) at Ludhiana.

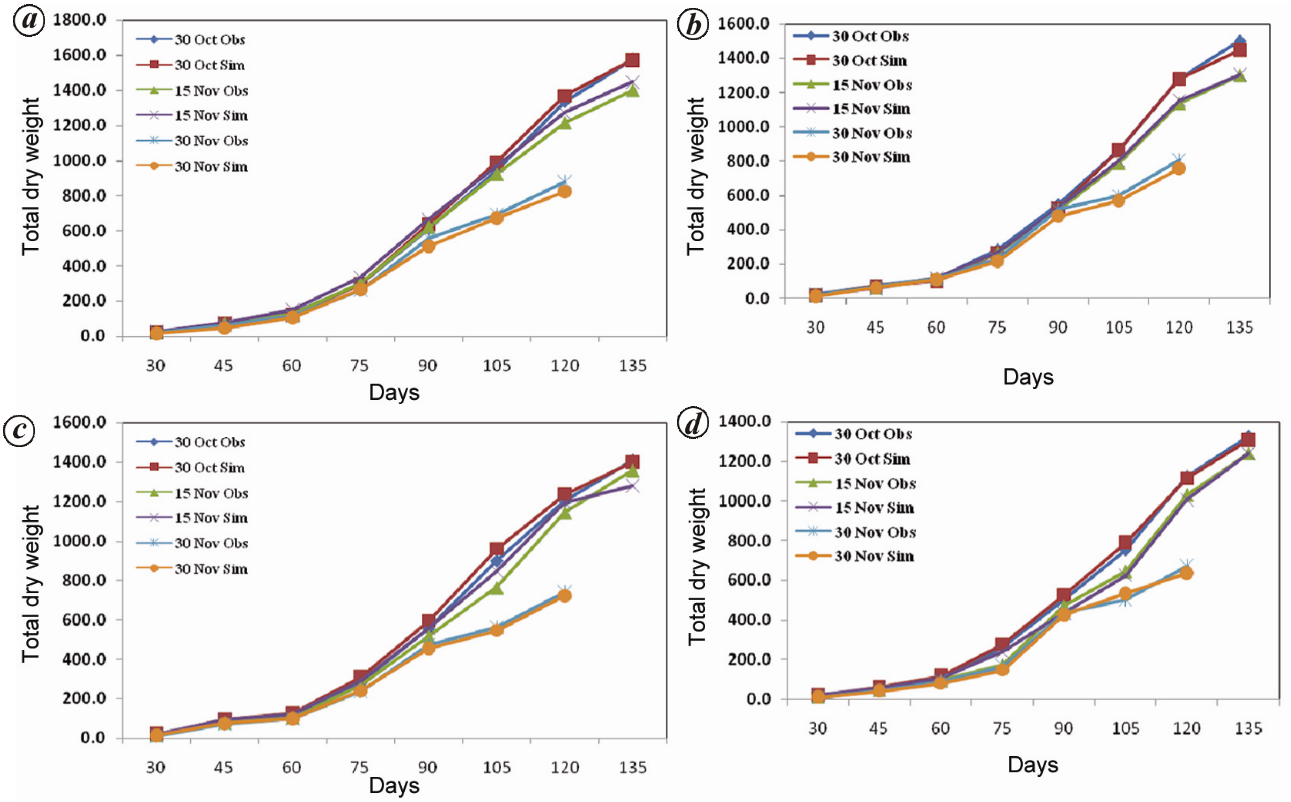

Figure 6. Validation between field-experimental and simulated total dry weight of cultivars (***a***) PBW 343; (***b***) PBW 542 (2008–09) and (***c***) PBW 343; (***d***) PBW 542 (2009–10) at Ludhiana.

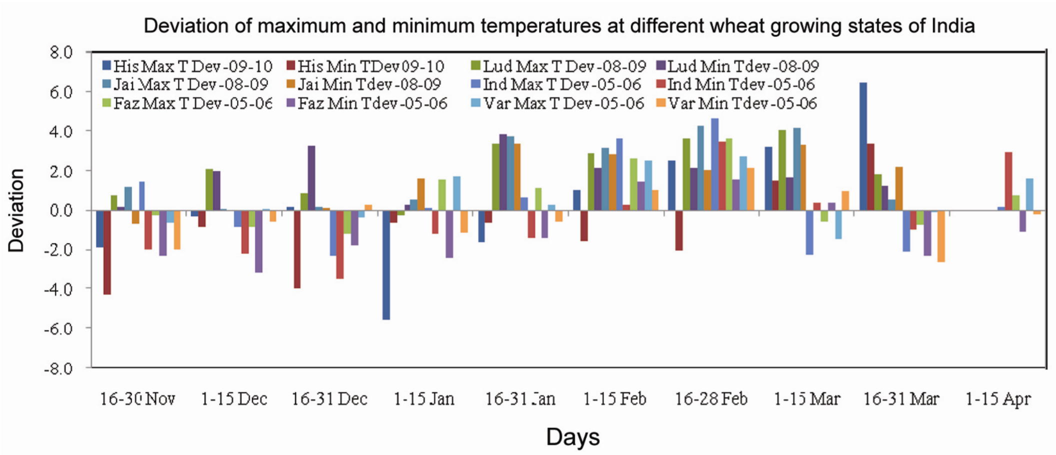

Figure 7. Deviation (%) maximum and minimum temperature at the selected wheat growing states of India.

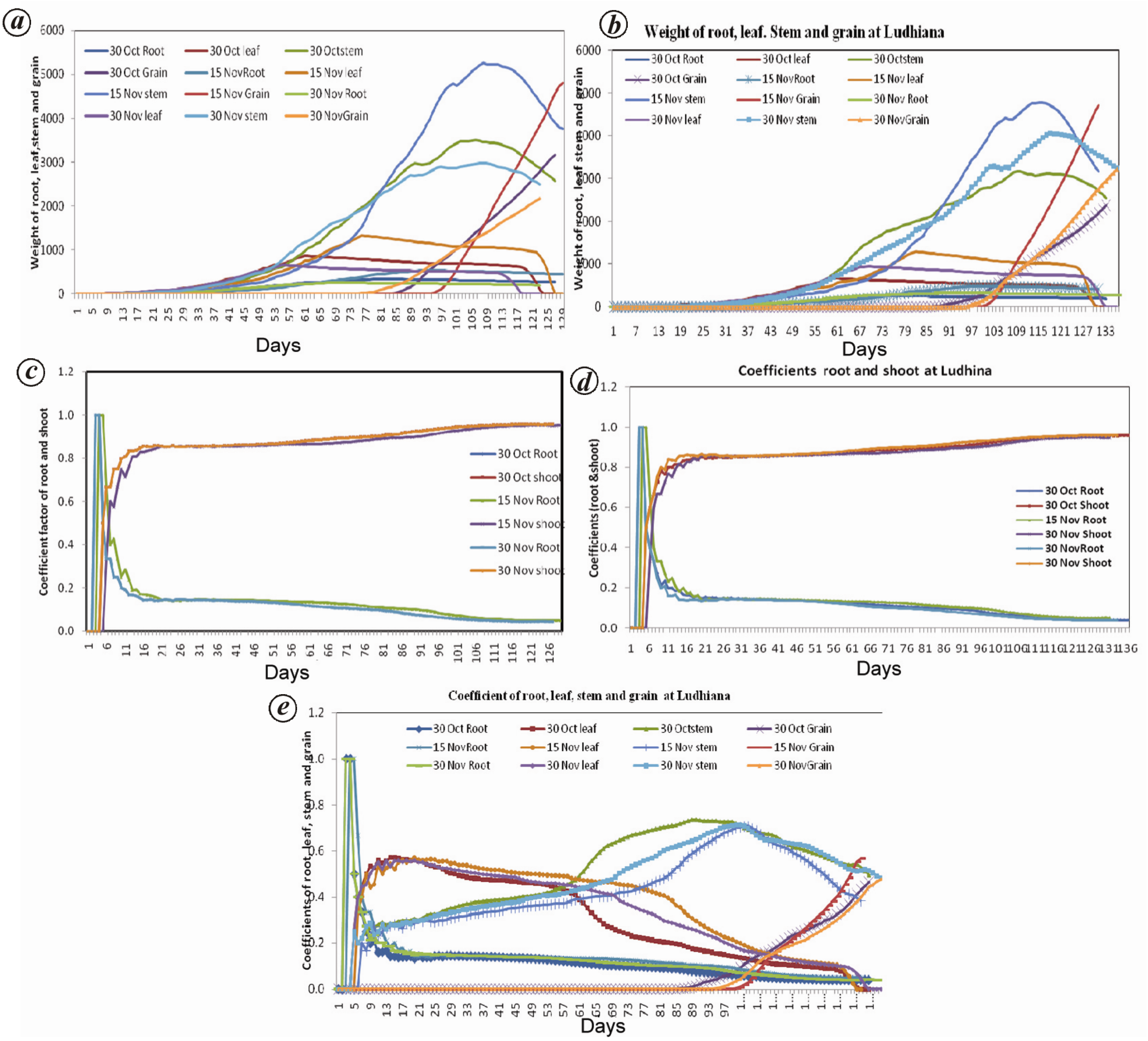

Figure 8. (***a***) Weight of partitioning (2008–09), (***b***) weight of partitioning (2009–10), (***c***) coefficient of root and shoot (2008–09), (***d***) coefficient of root and shoot (2009–10) and (***e***) coefficient of root, leaf, stem and grain cultivar PBW 343 (2008–09) for different sowing days at Ludhiana.

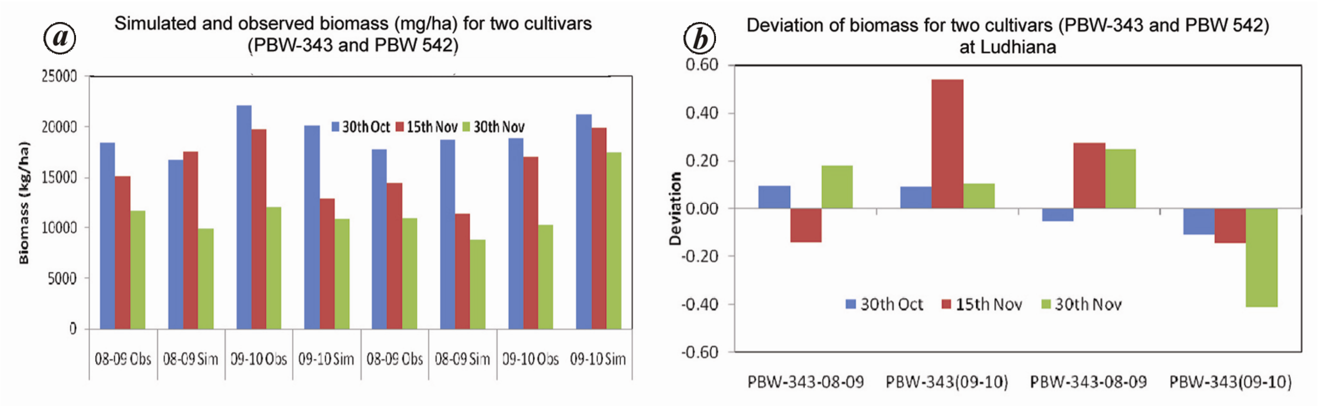

Figure 9. (***a***) Validation between simulated and field-experimental biomass (kg/ha) and (***b***) deviation (%) at Ludhiana.

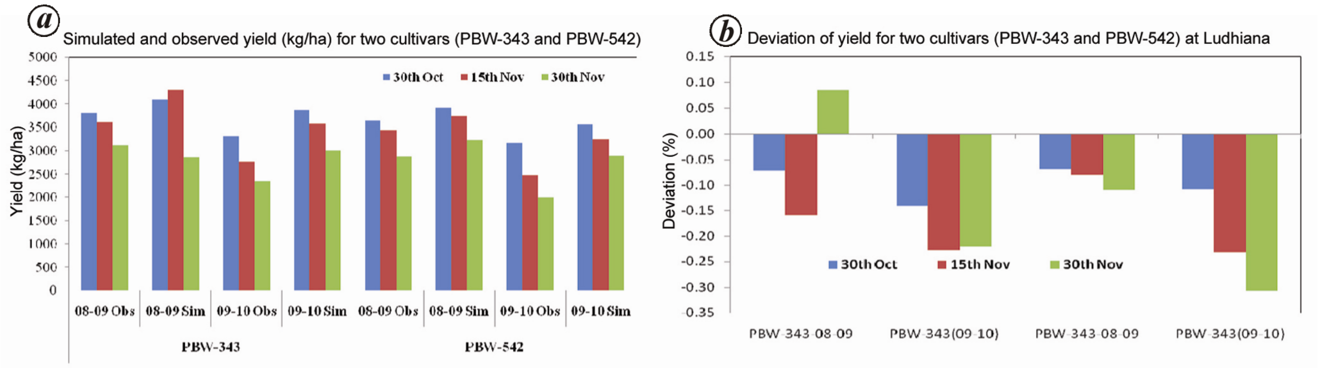

Figure 10. (***a***) Validation between simulated and field-experimental wheat yield (kg/ha) and (***b***) deviation (%) at Ludhiana.

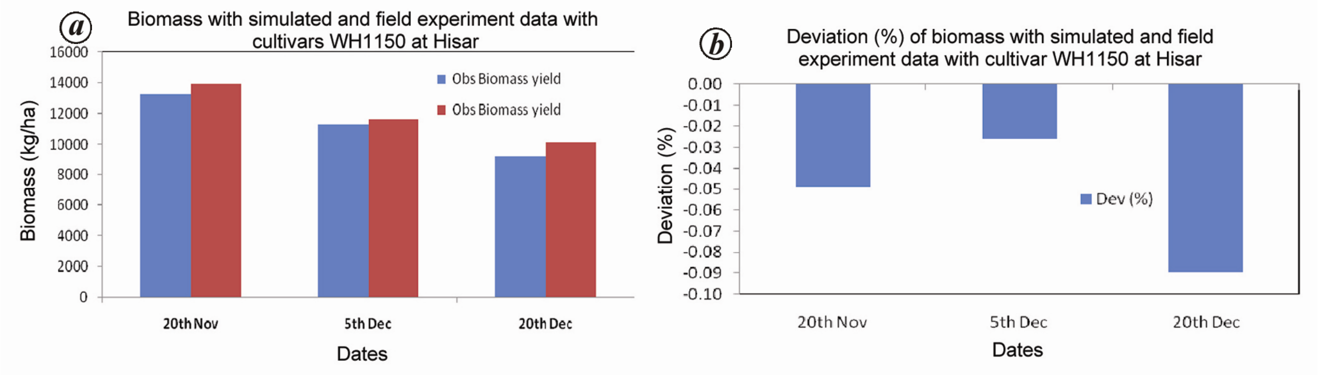

Figure 11. (***a***) Validation between simulated and field-experimental biomass (kg/ha) and (***b***) deviation (%) at Hisar.

years. On the other hand, the biomass weight of cultivar PBW 542 was overestimated for the first sowing date and underestimated for the second and third sowing dates with respect to simulated biomass (Figure 9 *a*). The overall biomass of cultivar PBW 343 was less compared to cultivar PBW 542 during both the years (Figure 9 *b*). The higher grain yield from the plant types was mainly due to more grains per spike and heavier individual grain weights. Increases in both the components might have helped by increased assimilate distribution to developing grain and less to stems, giving a higher grain yield[32,36]. The simulated yield showed overestimation from field-experimental yield for the first and second sowing dates and underestimation for the third sowing date for cultivar PBW 343. In case of cultivar PBW 542, the field-experimental yield was overestimated from simulated yield for all sowing dates (Figure 10 *a*). The overall validation of cultivar PBW 343 showed less deviation

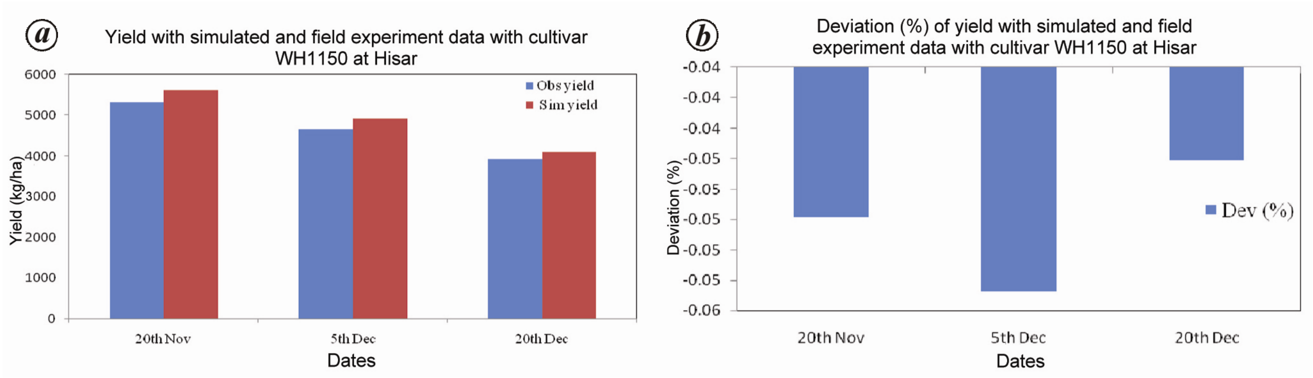

Figure 12. (***a***) Validation between simulated and field-experimental yield (kg/ha) and (***b***) deviation (%) at Hisar.

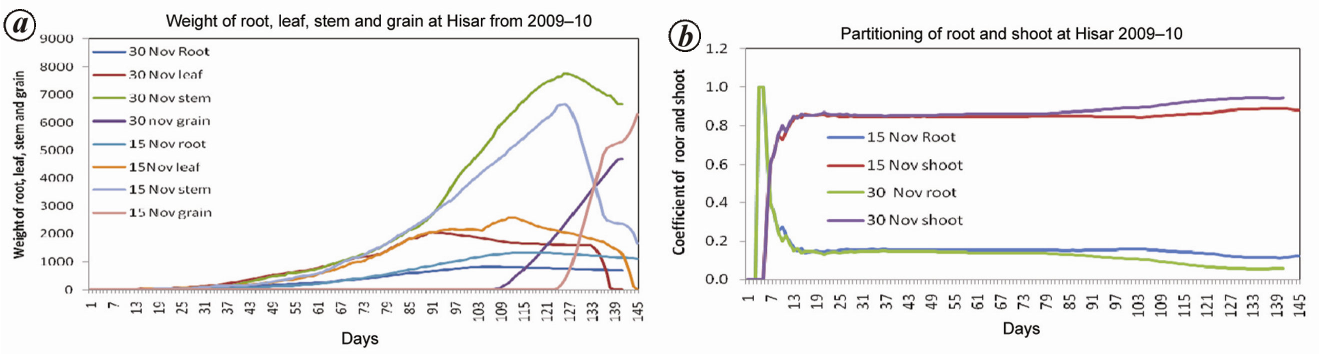

Figure 13. Simulated of (***a***) weight of partitioning and (***b***) coefficient of root and shoot for different sowing days (2009–10) at Hisar, Haryana.

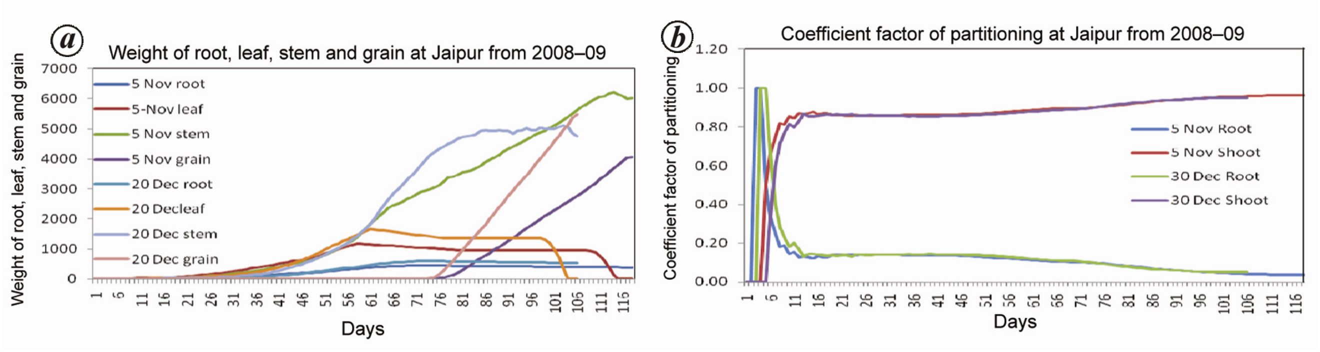

Figure 14. Simulated of (***a***) weight of partitioning and (***b***) coefficient of root and shoot for different sowing days (2008–09) at Jaipur, Rajasthan.

compared to cultivar PBW 542 during both the years (Figure 10 *b*). In general, both the field-experimental and simulated yield of cultivar PBW 343 was higher in field-experimental and simulated yield compared to cultivar PBW 542. Both the field-experimental and simulated yield data for the two cultivars, viz. PBW 343 and PBW 542 were fewer than three dates of sowing during both the years (Figure 10 *a*) at Ludhiana. A perusal of data on biomass reveals the case of grain yield, except PBW 542 under 30 October, which has slightly higher biomass yield compared to the other cultivars. The early sown dates have higher total biomass compared to late sowings date during both the years. The correlation coefficients of the field experimental and simulated yield and biomass vary from 0.81 and 0.96 respectively, and are found significant. The partitioning weights for leaf, stem and grain at few stages in the growth and development of wheat crop (PBW 343 and PBW 542) have been reported from the experimental sites and found to be consistent with those simulated by the model at Ludhiana[29,32,36]. The lower yield in cultivar PBW 542 compared to PBW 343 both in simulation and field-experiments could be attributed to suppressed biomass production subsequent to the end of leaf stages (40 days) as a consequence of temperature

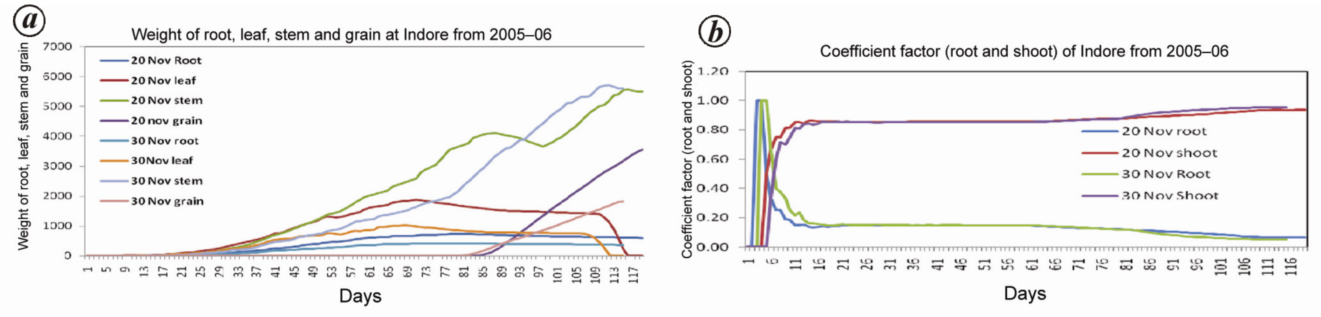

Figure 15. Simulated of (***a***) weight of partitioning and (***b***) coefficient of root and shoot for different sowing days (2005–06) at Indore, Madhya Pradesh.

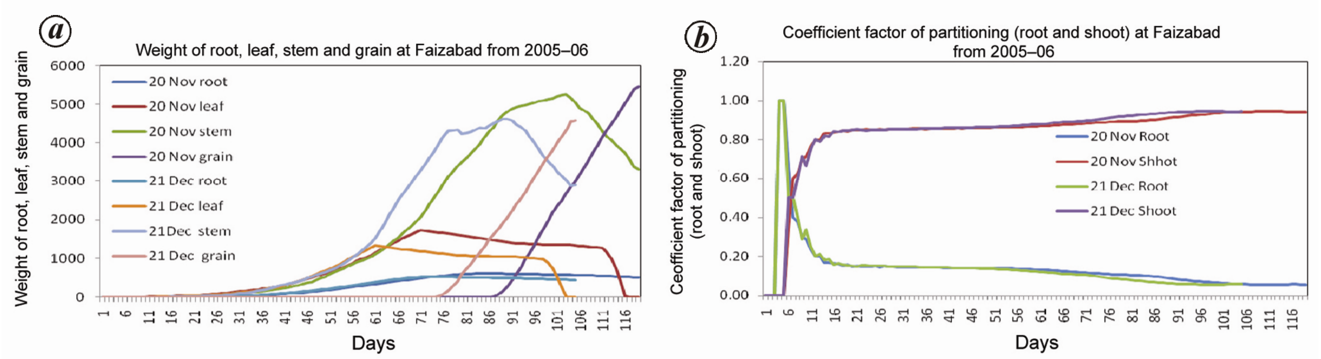

Figure 16. Simulated of (***a***) weight of partitioning and (***b***) coefficient of root and shoot for different sowing days (2005–06) at Faizabad, Uttar Pradesh.

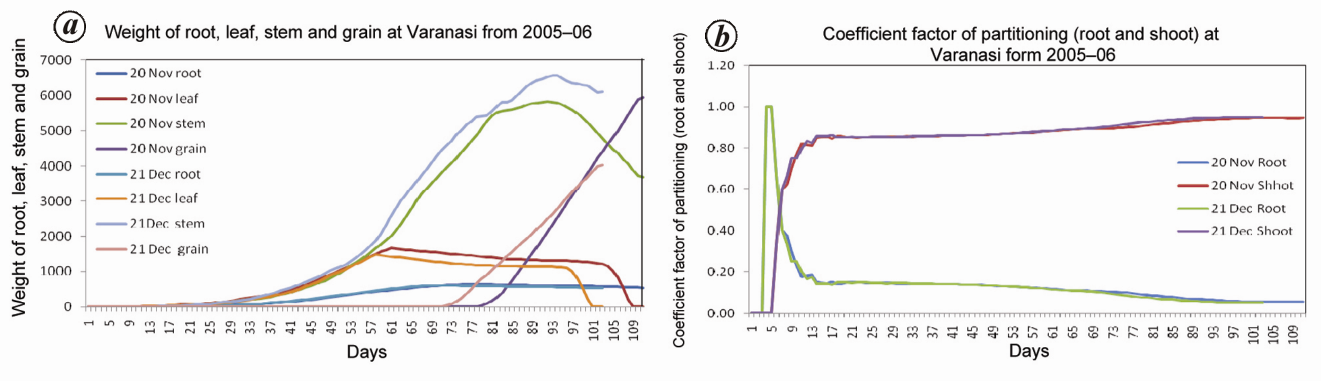

Figure 17. Simulated of (***a***) weight of partitioning and (***b***) coefficient of root and shoot for different sowing days (2005–06) at Varanasi, Uttar Pradesh.

(maximum and minimum) increase during the later stages of growth. Though the temperatures were above normal from end February to end March, the nighttime temperature was comparatively cooler than the daytime temperature (Figure 7). Hence the grain-formation stage was not adversely affected in wheat crop. The rainfall received during the vegetative growth period of *rabi* season was also favourable as it helped in the establishment of good crop stand in 2008–09. In general, the weather was conducive for the *rabi* season crops such as wheat. The higher heat unit anomalies considerably slowed down the potential reproductive growth leading to poor biomass production and low yields in PBW 542 during both the years (Figure 10 *a*). Higher normal daytime temperature lowered the LAI in PBW 343, while lower normal night temperature led to higher LAI during the flowering to end leaf stages of crop development in cultivar PBW 542 (Figure 7). During the 2009–10 *rabi* season, the sunshine hours were invariably below normal up to mid February by nearly 0.5–5.9 h. Later, they became near normal and were above normal in March. From the weather point of view, the early part of *rabi* season, 2008–09 was the favourable year for the early (October) and normal (November) sown wheat crop. The temperatures (maximum and minimum) remained ±2°C near normal. This proved beneficial for the early vegetative stage as it led to prolonged tillering stage. However, wheat crop sown after the third week of November up to mid-December experienced low temperature stress during the early vegetative growth period. With the start of the tillering stage (during mid-January up to February), the temperatures became near or above normal (Figure 7). It was coincided with the anthesis and grain filling stage in early and normal sown wheat crop. During March, the temperatures were above normal by 4°–6°C. This period was critical for early, normal and late-sown wheat crop as grain filling and grain growth were sensitive to high temperature in 2009–10 (ref. 36).

Yield attributes at Hisar

The field-experimental anthesis and physiological maturity day were attained in 97 and 144; 98 and 139; 103 and 133 days, but simulated anthesis and maturity day were attained in 102 and 138; 105 and 133; 108 and 128 days in 20 November, 5 December and 20 December dates of sowing and was computed. The anthesis day of simulated was overestimated from field-experimental day, and the maturity day of simulated day was underestimated from field-experimental day. The field-experimental yield and biomass with simulated yield and biomass were under 20 November, 5 December and 20 December dates of sowing (Figures 11 *a*–12 *b*). This proved beneficial for the early vegetative stage as it led to prolonged tillering stage. However, wheat crop sown after the third week of November up to mid-December experienced low temperature stress during the early vegetative growth period due to the temperatures (maximum and minimum) remained ±2°C near normal (Figure 7). The field-experimental yield and biomass of the cultivar WH 1150 were underestimated from the simulated yield and biomass, and deviation was less than 8 (Figures 11 *a*–12 *b*)[32,36]. The correlation coefficient between field-experimental and simulated yield and biomass varied from 0.94 and 0.95 and was found significant.

Partitioning of dry mater

The CERES-wheat model was used on wheat crops from selected year and wheat growing districts, i.e. Hisar–2008–09; Jaipur–2005–06; Indore–2005–06, Faizabad–2006–07 and Varanasi–2005–06 with the above mentioned wheat cultivars for three sowing dates mentioned in Table 1. The partitioning of root, leaf, stem and grain of the weight for various components of wheat crop from sowing to harvesting for the selected years and districts is shown in Figures 13 *a* to 17 *b*. The weight of root was increased from sowing to tillering stage then decreased due to the leaf weight. The leaf weight was increased from tillering stage to heading stage in Hisar (Figure 13 *a*), but the weight of root also started increasing from sowing days to tillering stages and heading stage at Jaipur (Figure 14 *a*). After a decrease in root and leaf weight, stem and grain weight started increasing from reproductive to harvesting stage in both districts (Hisar and Jaipur). The weight of root, leaf, stem and grain also decreased from sowing to harvesting stages at Indore, Faizabad, Varanasi (Figures 15 *a*–17 *a*) compared to Hisar and Jaipur districts (Figures 13 *a*–14 *a*). The partitioning of the photosynthesis assimilates to grain was higher for Hisar, which led to higher biomass production and hence better crop yield was used in the simulation model than at Jaipur. The partitioning of dry matter of plant parts was brought out of the leaf water content rather than the photosynthetic capabilities in terms of leaf area and total dry matter production. The increased weight in late sowing was because of higher temperature (2°–3°C) during late vegetative and reproductive phase, which caused early phonological growth and development and reduced crop duration and total biomass. Coefficients of root increased from tillering stage and then increased shoot coefficients (leaf, stem and grain) in reproductive stages to harvesting at Jaipur, Indore, Faizabad, Varanasi than Hisar (Figures 13 *b*–17 *b*). The percentage of dry matter accumulation (roots, leaf and stem) was due to delay in sowing for all selected districts. The increased temperature during the reproduction phase under delayed sowing was due to early completion of the required thermal unit of anthesis and maturity. These strong sources (leaves and stems) may also help produce higher grain yield due to their large capacity to mobilize more pre-anthesis assimilation to grain. It was found that higher biomass yield and its greater partitioning into roots and grain spikes resulted in higher grain yields[29–33]. The coefficient of shoot always showed an increase due to larger partitioning of the photosynthetic assimilates to roots, leaves, stems of grain obtained of the selected stations (Figures 13 *b*–17 *b*). If the daily pool of carbon is insufficient to allow potential growth, a fraction of carbon can be remobilized from the vegetative to reproductive sinks each day. Kernels are allowed to grow until physiological maturity is reached. Likewise, if the grain growth rate is reduced below a threshold value for several days, growth is also terminated. For additional details on the CERES model, see refs 34, 35.

Climatic variability

The CERES-wheat model data were simulated for 23 years (1990–14) weather data for three sowing days. The comparison between simulated yield and observed yield is shown in Figure 18. The simulated yield and districts yield were highest in Ludhiana among all the selected

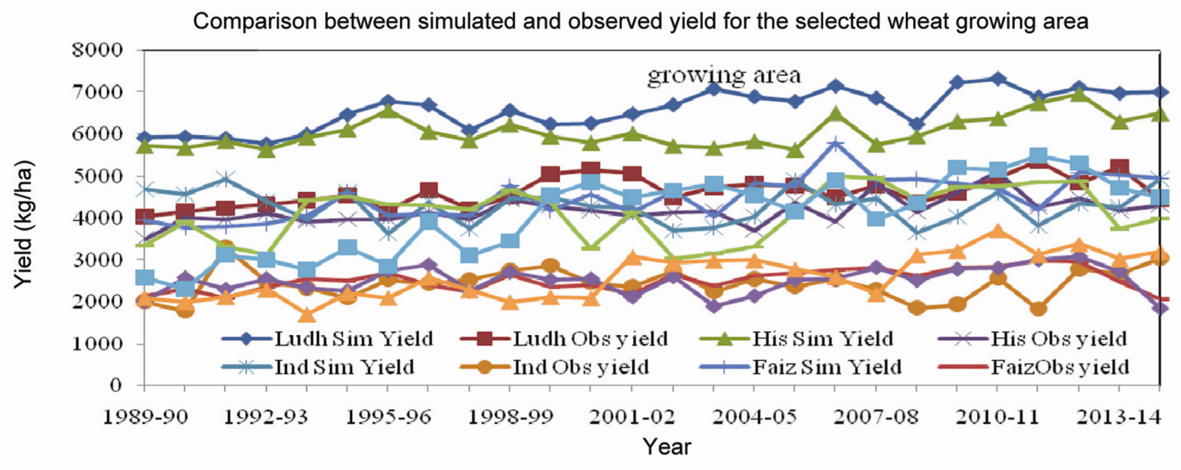

Figure 18. Comparison between simulated and observed yield (kg/ha) at the selected wheat growing states of India.

Table 2. Basic statistical characteristics of simulated and observed yield at selected wheat growing states (1990–2014)

	Ludhiana		Hisar		Jaipur		Indore		Faizabad		Varanasi	
Stations/statistical analysis	S	O	S	O	S	O	S	O	S	O	S	O
Mean yield (kg/ha)	6419	4645	5923	4186	4091	2607	4292	2438	4484	2513	4106	2506
SD (kg/ha)	357	356	411	331	941	539	400	372	502	261	638	325
CV (%)	5.6	7.7	6.9	7.9	23.0	20.7	9.3	15.3	11.2	10.4	15.6	13.0
Maximum yield (kg/ha)	6987	5375	6956	5098	5499	3720	4940	3300	5791	2973	4998	3079
Minimum yield (kg/ha)	5782	4046	5112	3498	2315	1702	2746	1788	3769	2060	3020	1851
R square	0.29		0.23		0.62		0.17		0.28		0.28	
Correlation coefficient	0.53		0.48		0.78		0.41		0.53		0.53	

S, Simulated yield. O, Observed yield.

districts. The simulated yield increased from 5782 to 6987 kg ha^{-1} with mean yield of 6419 kg ha^{-1} and the standard deviation (SD) of 357 kg ha^{-1} and the coefficient of variation (CV) of 5.6%. However, district yields increased significantly over time and ranged from 4046 to 5375 kg ha^{-1} with mean of 4645 kg ha^{-1}, CV of 7.7% and SD of 331 kg ha^{-1} (Figure 18 and Table 2) at Ludhiana[32,37–39]. In Hisar district, the simulated yield ranged from 5112 to 6956 kg ha^{-1} with mean yield of 5923 kg ha^{-1}, SD was 411 kg ha^{-1} and CV was 6.9%. The district yield of Hisar ranged from 3498 to 5098 kg ha^{-1} with the mean of 4186 kg ha^{-1} and SD was 331 kg ha^{-1} and CV was 7.9% (refs 32, 37–39). The simulated yield ranged from 2315 to 5499 kg ha^{-1} with the mean yield of 4091 kg ha^{-1}, SD of 941 kg ha^{-1} and CV of 23.0% at Jaipur. The district yield of Jaipur ranged from 1702 to 3720 kg ha^{-1} with a mean yield 2607 kg ha^{-1}, SD of 539 kg ha^{-1} and CV of 20.7%. The simulated yield ranged from 2746 to 4940 kg ha^{-1} with mean of 4292 kg ha^{-1} and SD of 400 kg ha^{-1} and CV of 9.3% at Indore district. The district yield of Indore ranged from 1788 to 3300 kg ha^{-1}, with mean of 2438 kg ha^{-1}, and SD was 372 kg ha^{-1} and CV was 15.3% (refs 27, 36–39). In Faizabad district, the simulated wheat yield ranged from 3769 to 5791 kg ha^{-1} with mean of 4484 kg ha^{-1}, SD of 502 kg ha^{-1} and CV of 11.2%. The district yield of Faizabad ranged from 2060 to 2973 kg ha^{-1} with mean of 2513 kg ha^{-1}, SD of 261 kg ha^{-1} and CV of 10.4% (refs 32, 37–39). In Varanasi district, the simulated yield ranged from 3020 to 4998 kg ha^{-1} with mean of 4106 kg ha^{-1}, SD of 638 kg ha^{-1} and CV of 15.6%. The district yield of Varanasi ranged from 1851 to 3079 kg ha^{-1} with mean of 2506 kg ha^{-1}, SD of 325 kg ha^{-1} and CV of 13.0% showed (Figure 18 and Table 2). The correlation coefficients between simulated and observed yield varied from 0.41 to 0.78 in all the six districts (Table 2). The temperatures, both maximum and minimum, remained ±2°C near normal. This proved beneficial for the early vegetative stage as it led to prolonged tillering stage. However, wheat crop sown after third week of November up to mid-December experienced low temperature stress during the early vegetative growth period. With the start of the tillering stage (during mid-January up to February), the temperatures became near or above normal (Figure 16 *b*). Although the model realistically simulates the year-to-year variations in yields, deviations in simulated and observed districts yields are due to increase in temperature and decreases in anthesis and milking stages.

Conclusion

In this study, the highest yield was obtained when wheat was sown on 15 November, which declined sharply under first and third sowing date during both the years at Ludhiana. The computed correlation coefficients between the field-experimental and simulated phenological stages data varied from 0.70 to 0.96 at Ludhiana. The wheat crop attained peak LAI between 90 and 105 days under all the sowing days. The simulated LAI was overestimated compared to field-experimental LAI at Ludhiana. The coefficient of root and shoots (leaf, stem and grain) decreased up to 30 days and thereafter increased (root and shoot coefficients) up to harvesting. After the decrease in the root and leaf coefficients, the stem and grain coefficients started increasing up to harvesting of the crop for both the years due to the partitioning of the photosynthates assimilation toward grain. It was higher in cultivar PBW 343 in 2008–09, which led to higher biomass production and hence better crop yield in simulation than during 2009–10. The field-experimental yield was underestimated compared with simulated yield and the deviation showed good accuracy (error % less than 8). The correlation coefficient between field-experimental and simulated yields with biomass varied from 0.81 and 0.96 at Ludhiana, and varied from 0.94 and 0.95 at Hisar. The coefficient of shoot showed increased coefficient factor due to larger partitioning of the photosynthate assimilation to roots, leaf, stems of grain obtained as compared to Hisar, Jaipur, Indore, Faizabad and Varanasi. The partitioning of the photosynthates assimilation to grain was higher than Hisar which led to higher biomass production and hence better crop yield in simulation. Thus it has been observed that the temperature may strongly influence crop growth, biomass and yield. High temperature during anthesis to milking may increase photosynthesis, resulting in lower yield in early and delayed sowing date. The correlation coefficients between simulated yield and districts yields varied from 0.41 to 0.78 for all selected districts. CERES-wheat will continue to evolve as new applications are developed and we learn to effectively incorporate other factors for a more comprehensive agricultural systems analysis. Further, we need to validate the simulated data and field-experimental data of Hisar, Jaipur, Indore, Faizabad and Varanasi.

Limitations

The model does not include the other nutrient factors, i.e. phosphorus, potassium and plant essential micronutrients. These nutrients and micronutrients are assumed to be in abundant supply in the soil so as not to cause any stress on the crop, which is often not true. Similarly, losses due to weeds, pests and diseases are also not included in the model. Due to favourable weather conditions, pest infestation and diseases may cause losses to the crops, which cannot be simulated at present using the model.

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