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Calibration and Validation of DSSAT Model for Simulating Wheat Yield in Bangladesh

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Abstract: Crop simulation models are used in predicting crop productivity under various crop management options and changing climatic parameters that require determination of genetic coefficient of a crop cultivar. Successful use of a crop model depends on the accuracy of calibration and validation of different parameters. This paper aimed to evaluate the DSSAT (v4.6) crop model in Bangladesh for wheat production. Genetic co-efficient of four wheat cultivars (BARI Gom-25, 26, 27 & 28) were determined through DSSAT model. Experimental data on irrigation and nitrogen effect on wheat production was used for model calibration and date of sowing effect for model validation. Model evaluation results showed closer estimation of crop growth duration, grain and biomass yields. Percent error difference in grain yield of wheat varieties (BARI Gom- 25, 26, 27 and 28) between simulated and observed values were 10.98%, 8.70%, 10.79% and 8.94%, respectively. Relationship between simulated and observed grain yields, and simulated and observed crop duration both at calibration and validation process are strong having higher R^2 value. The model has been successfully calibrated and validated for wheat growing in Bangladesh environment and can now it can be taken for further applications in natural resources management and climate change impact studies.
Keywords: Calibration, Validation, DSSAT Model, Wheat, Bangladesh.

INTRODUCTION

Wheat is the second most important cereal crop in Bangladesh [1]. It is very much sensitive with climatic parameter specially temperature.

Though it is cultivated in winter, the season is very short. So, wheat crop suffer from higher temperature at the later part of crop growth and development. Yield also depends on various management options like date of sowing and irrigation, etc. Bangladesh Agricultural Research Institute developed 30 wheat cultivars. Of them, BARI Gom-25, 26, 27 and 28 are latest and tolerant to different stress conditions [2].

Crop models are effective tools to predict crop productivity under different management options and climatic conditions. In the contest of climate change, importance of crop model in simulating crop production under different climatic scenario was increasing day by day [3, 4]. Bangladesh agriculture is highly vulnerable in the contest of climate change. About 4.1% wheat grain yield will reduced if 1^{o}C temperature rise [2]. Successful use of crop model depends on proper calibration of models. Determination of genetic coefficient of a cultivar can be obtained from proper model calibration. Calibrated crop models with cultivar parameters can be used to optimize crop management [5] to evaluate the impacts of climate change [6] or to develop options and to optimize resource use [7].

DSSAT is a popular crop model used over 100 countries for more than 20 years [6]. It is a microcomputer software package, that provides a shell program for the interface of crop-soil simulation models, data for soil and weather, and programs for evaluating management strategies. DSSAT includes more than 40 crop growth model. Among them, CERES-Wheat is most widely used crop simulation model. Crop modelling study especially DSSAT on different crops is meagre in Bangladesh. Cultivar coefficients of popular wheat varieties of Bangladesh are not included in the cultivar database of DSSAT [8]. Therefore this study was undertaken: i) to generate genetic co-efficient of wheat cultivars required for running of DSSAT model in Bangladesh condition and ii) to calibrate and validate DSSAT crop model for simulation of growth and yield of wheat.

MATERIALS AND METHODS

Site description

The study was conducted at Bangladesh Agricultural Research Institute. Gazipur and Dinajpur were the experimental locations. Gazipur is located at 23.59° N and 90.24° E and 8 m above mean sea level and Dinajpur is located at 25.63° N and 88.63° E and 39 m above mean sea level.

DSSAT (CERES-Wheat) Model

DSSAT v4.6 was used for simulating wheat yields in growing environments of Bangladesh. The model runs with five sets of data: i. Soil file, ii. Weather file, iii. Genetic coefficients, iv. Experimental (X) file, v. Time course (T) file and vi. Annual (A) file. Soil data included soil characteristics such as site latitude and longitude, soil type and soil series, pH, bulk density, soil texture and soil N and C content (Table-2 and 3). Weather file included temperature (both maximum and minimum), humidity, sunshine hours, rainfall (Figures 1a for Gazipur and 1b for Dinajpur). DSSAT model required some of crop management data [crop, cultivar, planting date, row and plant spacing, fertilizer levels, tillage practices and organic amendments [6] in experimental file to simulate crop productivity. Data on physiological stages of crop growth such as anthesis dates, days to maturity and grain yield were also included in A and T files. In order to simulate yields under future climate scenarios, first the CERES-Wheat module in DSSAT was calibrated and validated for this study. Climatic data were collected from the weather station of Department of Metrology of Bangladesh Government. The crop management data were recorded throughout the growing seasons. The input files, such as weather file, soil file, and A & T files, were created for running of the model. The model were calibrated with set of field experimental data and subsequently validated with another dataset of field experiments. Seven characters of wheat were needed in CERES-Wheat model in DSSAT (Table-1).

Table-1: Description of different genetic characters of wheat for use in model

Name of parameters	Definition
P1V	Days, optimum vernalizing temperature, required for vernalization
P1D	Photoperiod response (% reduction in rate/10 h drop in pp)
P5	Grain filling (excluding lag) phase duration (^oC-d)
G1	Kernel number per unit canopy weight at anthesis (#/g)
G2	Standard kernel size under optimum conditions (mg)
G3	Standard, non-stressed mature tiller weight (incl grain) (g dwt)
PHINT	Interval between successive leaf tip appearances (^oC-d)

Soil Properties

Initial soil of experimental field were collected from a depth of 0-15, 15-30, 30-60, 60-90, 90-120 and 120-150 cm. These soil samples were analysed for textural class, bulk density, pH, organic carbon, total N, NO_3^-N, NH_4^+N, available phosphorous and available potassium using standard analytical methods. The experiments were laid out in Grey Terrace Soil of Gazipur and Grey Floodplain Soil of Dinajpur. Nutrient status of experimental fields was mentioned in Tables 2a & 2b for Gazipur location and Tables 3a & 3b for Dinajpur location.

Table-2a: Physical properties of experimental soil (Gazipur location)

Soil layer (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (Mg m^{-3})
0-15	30.84	46.42	22.74	1.52
15-30	20.84	47.35	31.81	1.53
30-60	20.48	40.24	39.28	1.56
60-90	23.48	43.71	32.81	1.57
90-120	19.84	42.35	37.81	1.61
120-150	18.84	45.21	35.95	1.63
150-180	19.36	46.28	34.36	1.66

Table-2b: Chemical properties of experimental soil (Gazipur location)

Soil layer (cm)	pH	Organic carbon (%)	Total N (%)	NO_3^-N (mg kg^{-1})	NH_4^+N (mg kg^{-1})	Available P (mg kg^{-1})	Available K (meq $100g^{-1}$)
0-15	5.6	1.04	0.11	11.4	1.8	9.06	0.29
15-30	5.8	0.93	0.09	9.8	2.0	8.78	0.27
30-60	5.9	0.77	0.08	7.6	2.2	7.11	0.24
60-90	6.0	0.52	0.06	6.4	2.4	5.63	0.22
90-120	6.1	0.46	0.05	5.3	2.6	5.09	0.18
120-150	6.2	0.41	0.04	4.9	2.8	3.89	0.15
150-180	6.3	0.36	0.03	4.1	2.9	3.21	0.14

Table-3a: Physical properties of experimental soil (Dinajpur location)

Soil layer (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (Mg m^{-3})
0-15	61.0	22.7	16.3	1.49
15-30	66.3	11.7	27.3	1.57
30-60	58.3	11.0	30.7	1.59
60-90	55.9	9.4	34.7	1.61
90-120	67.3	14.4	18.3	1.62
120-150	74.3	6.4	19.3	1.67
150-180	74.3	6.3	19.4	1.69

Table-3b: Chemical properties of experimental soil (Dinajpur location)

Soil layer (cm)	pH	Organic carbon (%)	Total N (%)	NO_3^-N (mg kg^{-1})	NH_4^+N (mg kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})
0-15	6.1	0.49	0.05	9.8	2.0	6.27	0.26
15-30	6.2	0.28	0.03	7.3	2.1	6.03	0.24
30-60	6.2	0.19	0.02	5.1	2.2	5.18	0.22
60-90	6.3	0.14	0.01	4.7	2.5	4.83	0.19
90-120	6.4	0.13	0.01	4.3	2.7	3.98	0.16
120-150	6.5	0.12	0.01	3.5	3.2	3.19	0.15
150-180	6.7	0.10	0.01	3.0	3.4	2.88	0.13

Weather data

Daily weather data for both the growing seasons, including precipitation (mm), minimum and maximum air temperatures (°C), and global solar radiation (MJ m^{-2}) was calculated from daily sunshine hours using Weatherman of DSSAT v4.6. Maximum, minimum and average temperature, rainfall, relative humidity and sunshine hour of both experimental sites are presented in Figures 1a & b.

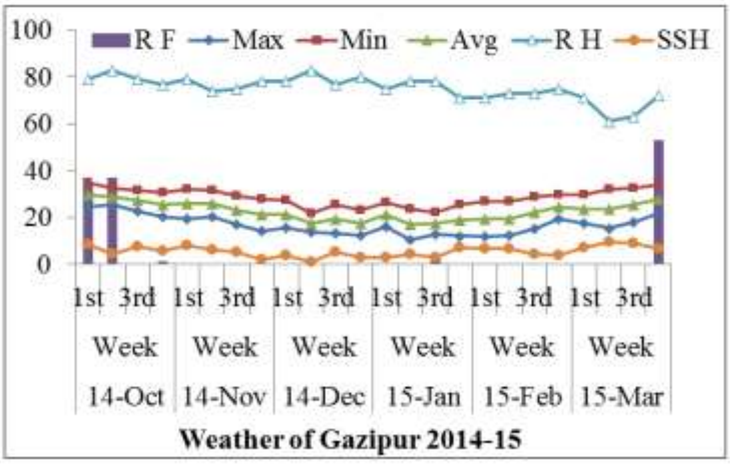

Fig-1a: Weather data of experimental site at Gazipur

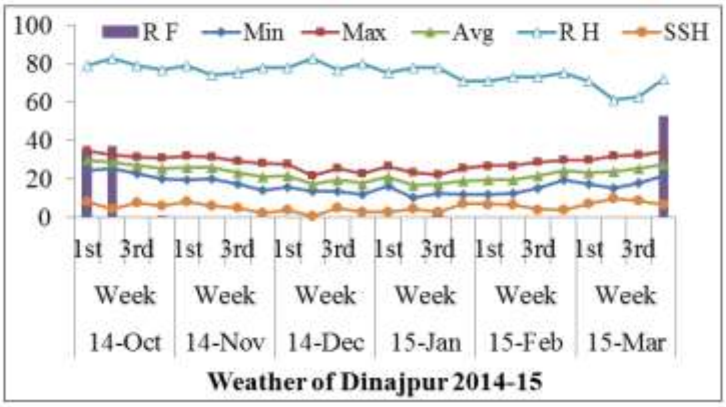

Fig-1b: Weather data of experimental site at Dinajpur

Field experiments for model calibration and validation

One set of experiment (irrigation and N effect on wheat) was used for model calibration during 2013-2014, which was conducted at Wheat Research Centre, Nashipur, Dinajpur. Another set of experiment on date of sowing effect on wheat yield was used for model validation during 2013-2014 that was conducted at BARI central farm at Gazipur. BARI Gom-25, 26, 27 and 28 were used as test varieties. Yield potentialities of these varieties ranges from 4.0 to 6.5 t ha^{-1}. Seed rate used was 120 kg ha^{-1}. Unit plot size was 3.0 m x 2.4 m. Yield and yield contributing related data were recorded. Harvested area was 2.4 m^2. Nitrogen, P, K, S, Zn and B were applied at the rate of 100, 27, 60, 20, 5 and 1 kg ha^{-1}. Urea, triple supper phosphate, muriate of potash, gypsum, zinc sulphate and boric acid were used as a source of N, P, K, S, Zn and B. One third of urea and all other fertilizers were applied during land preparation. The rest amounts of urea were applied in two equal splits at 20 and 50 days after sowing (DAS), respectively. Irrigation water was applied at 20, 50 and 75 DAS. Other intercultural operations like thinning, weeding, etc were done as and when necessary.

Crop growth and yield & its attributes

Phenology of wheat was determined by observing different growth stages. Germination was observed at 5-7 DAS. Crown root initiation (CRI) stage was observed at 17-21 DAS from 5-10 plants after collection with the help of spade at 15-30 cm depth from middle portion of each plot. Heading took place at 55-60 DAS, which was determined after observing 50% and above spikes emergence. Anthesis was observed at 60- 70 DAS. Physiological maturity (90-100 DAS) was noticed when the peduncle of 50% of spike became straw coloured. Phenology varied depending on variety.

Plant growth analysis

Leaf area was measured at germination, crown root initiation, maximum tillering, heading/anthesis and physiological maturity by an automatic area meter (LI 3100 C, LI-COR, USA). For dry matter partitioning, leaves, stem, reproductive part (spike) were separated and dried in an oven at 70^{o} C for 72 hours. Sunshine hours were collected from the Weather Station of Bangladesh Rice research Institute, adjacent to the experimental field. Sunshine hours were converted to solar radiation using Weatherman of DSSAT Crop Model. Photosynthetically active radiation (PAR) was assumed as 50% of solar radiation [9], which were used for radiation use efficiency calculation.

Yield and yield attributes

The crop was harvested at 10-12 days after physiological maturity from 10 m^2 considering middle portion of each plot. The bundle was sun dried for 3-5 days. For grain and biomass yield, the bundle was weighted with the help of digital top load balance and recorded. Then the bundle was harvested with the help of combined harvester followed by sun drying of grains 2-3 days and weighted with the help of digital balance and grain moisture content was determined. Grin yield was adjusted at 14% moisture level. Yield components, plant height and number of spikes m^{-2} were measured in the field. Lengths of spike, number of spikelets $spike^{-1}$, number of grains $spike^{-1}$, 1000-grain weight (g) were recorded from 10 randomly selected spikes excluding harvested area. Data were analysed by using MSTAT-C and mean separation were done in LSD method.

Statistical evaluation

Statistical analysis of the degree of coincidence between simulated and observed values were done by using Root Mean Square Error (RMSE) [10] and the ratio of RMSE over the average Mean Difference (MD) [11, 12]. The RMSE has been widely used as a criterion for model evaluation [13-17]. RMSE is calculated by:

$$\mathrm{RMSE} = \sqrt{1/N\sum(Oi - Pi)2}$$

Where P and O are the predicted and observed values for the observation, and N is the number of observation within each treatment. RMSE is measure of the deviation of the simulated from the measured values, and is always positive. A zero value is ideal. Lower value of RMSE is the higher accuracy of the model prediction.

Model calibration

DSSAT crop models require genetic coefficients, which are cultivar specific for describing processes related to growth and development and grain production. These coefficients allow the model to simulate performance of diverse genotypes under different soil, weather and management conditions [18]. The model was calibrated using field measured values of weather parameters, crop management and soil properties during the 2013–2014 cropping season (Dinajpur location) of the experiment. Genetic coefficients were estimated by using observed anthesis and physiological maturity data and grain yield of growing season of 2013-2014 (Dinajpur location) and the data of Gazipur location was used for subsequent model evaluation [19, 20]. Since neither of the cultivars was previously introduced in DSSAT, we created them in the genetic file. Initial values of the genetic coefficients were obtained from the medium maturity group cultivar NEWTON, already available in the DSSAT. The computed CSPs values for test cultivars were copied into the cultivar (CUL) file to operate the simulation. An iterative approach was used to obtain reasonable genetic coefficients through trial and error adjustments until there was a match between the observed and simulated dates of anthesis and physiological maturity and grain yield [17, 21]. The identified genetic coefficients were used for model evaluation. In this study, water and nitrogen balance simulation controls were switched on, to ensure that no stress for water or nitrogen was experienced in the course of crop growth.

Model evaluation

Model performance was evaluated by comparing the simulated versus observed values from the trial of 2013-2014 (Dinajpur and Gazipur locations). Data for model validation include days to heading, days to anthesis and days to physiological maturity, grain yield, single grain weight, and above ground biomass. Comparison between measured and predicted wheat yield showed good agreement.

RESULTS AND DISCUSSIONS

Cultivar specific genetic coefficients

Genetic co-efficient of wheat was determined for seven characters viz. P1V, PID, P5, G1, G2, G3 and PHINT. Description of the genetic co-efficient was described in Table 4. Genetic co-efficient of G1, G2 and G3 of wheat varieties were determined manually from field experiments on average basis. Putting this value in the GenCalc program from DSSAT model, genetic co-efficient of P1V, PID, P5 and PHINT were determined (Table-4).

Table-4: Genetic coefficient of different wheat varieties

Variety	P1V (Days)	P1D (% reduction in rate 10 h^{-1} drop in pp)	P5 (^oC. d)	G1 (#/g)	G2 (mg)	G3 (g dwt)	PHINT (^oC. d)
BARI Gom-25	0	92	725	23	46	3.6	70
BARI Gom-26	0	92	730	23	46	3.8	70
BARI Gom-27	0	93	740	24	46	3.9	70
BARI Gom-28	0	96	750	25	47	3.9	70

The genetic coefficients P1V for all varieties were 0, because wheat varieties grown in Bangladesh are spring wheat type that does not need vernalization. Genetic coefficient P1D for BARI Gom-25, 26, 27 and 28 were 92, 92, 93 and 96 days, respectively. BARI Gom-28 was the highest (750) genetic coefficient P5 which was followed by BARI Gom-27 (740) and BARI Gom-26 (730). The lowest genetic coefficient P5 (725) was obtained from BARI Gom-25 (740). Genetic coefficient G1 for BARI Gom-25, 26, 27 and 28 were 23, 23, 24 and 215 days, respectively. Similarly, genetic coefficient G2 for BARI Gom-25, 26, 27 were same i.e. 46; while for BARI Gom-28, it was 47. There was considerable variation among the cultivar in G3 but the PHINT were the same amongst the cultivars. Highest G3 (3.9g) was obtained in BARI Gom-28 and BARI Gom-27 and lowest G3 (3.6g) was obtained in BARI Gom-25. Higher G3 indicated heavier seed weight. Genetic coefficients, PHINT for all wheat variety were 70.

Calibration of DSSAT model

Calibration of DSSAT model was done by crop duration and grain yield of the wheat of the year 2012-2013 (Table-5).

Table-5: Indicators of goodness of fit for crop duration and grain yield of different wheat varieties for model calibration in 2012-13

Variety	Parameter	Sim.	Obs.	PE (%)	R^2	NRMSE	EF	d
BARI Gom-25	Crop duration	113	111	1.80	0.87	4.04	0.49	0.88
	Grain yield	4931	4443	10.98	0.63	0.98	0.98	0.99
BARI Gom-26	Crop duration	115	113	1.76	0.85	4.19	0.83	0.95
	Grain yield	4937	4542	8.70	0.82	0.52	0.99	0.99
BARI Gom-27	Crop duration	110	107	2.80	0.93	5.29	0.19	0.81
	Grain yield	5278	4764	10.79	0.86	0.55	0.99	0.99
BARI Gom-28	Crop duration	111	107	3.74	0.59	4.44	0.05	0.79
	Grain yield	5608	5148	8.94	0.89	0.18	0.99	0.99

Percent error differences (PE) for observed and simulated grain yields of wheat varieties were 10.98%, 8.70%, 10.79% and 8.94%, respectively for BARI Gom-25, 26, 27 and 28. Similarly, PE differences for crop duration were 1.80%, 1.76%, 2.80% and 3.74%, respectively. These PE values were within the acceptable range (below 15%).

Simulated and observed grain yield and crop growth duration of wheat during calibration process are shown in Figures 2 & 3, respectively. The 1:1 line graph was drawn showing observed yield in X-axis and simulated yield in Y-axis. Simulated grain yield and crop duration were highly correlated with observed grain yield and crop duration. Regression equation for simulated grain yield was Sim = 0.83*Obs + 722 and for duration was Y = 0.91X + 7.4.

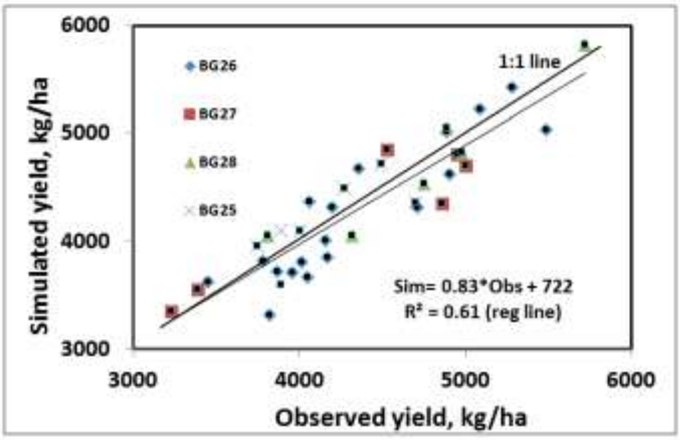

Fig-2: Observed and simulated grain yield of wheat during calibration process (Gazipur location)

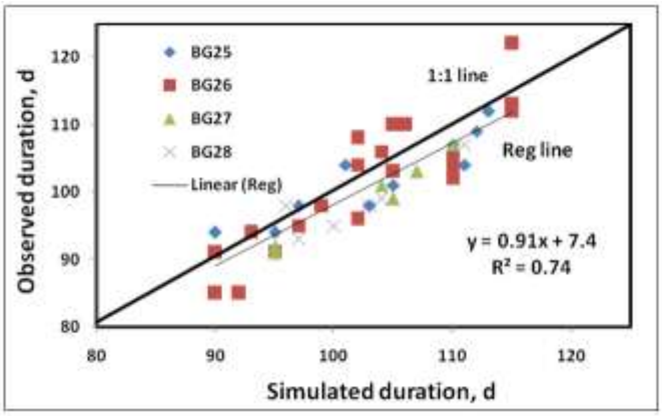

Fig-3: Observed and simulated crop duration of wheat during calibration process (Gazipur location)

Simulated and observed biomass yield at different growth stages at calibration process are shown in Fig. 4. Simulated biomass yield fitted well with observed biomass yield although simulated biomass yield was slightly higher than the observed values. Observed biomass yield increases with the advancement of crop growth duration and maximum biomass yields were obtained at 110 DAS. A typical biomass yield pattern begins with a slow increase at the initial stage, followed by a rapid increase at middle stage until a maximum value is reached. Biomass yield then decline as the leaves senesce and plants reaches maturity.

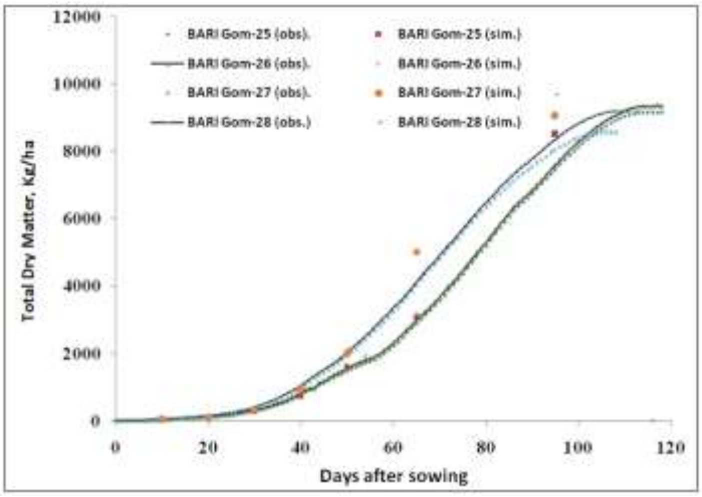

Fig-4: Observed and simulated biomass yield (y-axis, kg/ha) of wheat during calibration process (for Gazipur location)

Validation of DSSAT model

Figures-5 and 6 are showing relationships between simulated and observed grain yields and crop growth durations, respectively during validation processes. The regression line of grain yield was near to 1:1 line, indicating that the model was performing well under the test environment. The coefficient of determination (R^2) was around 82% in case of trend line. Simulated crop duration was also matched with observed crop duration. Regression equation for simulated crop duration = 0.82 X crop duration + 18.

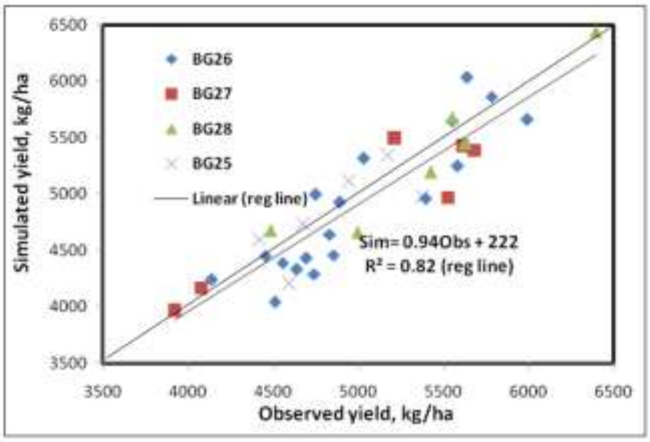

Fig-5: Observed and simulated grain yield of wheat during validation process (Dinajpur location)

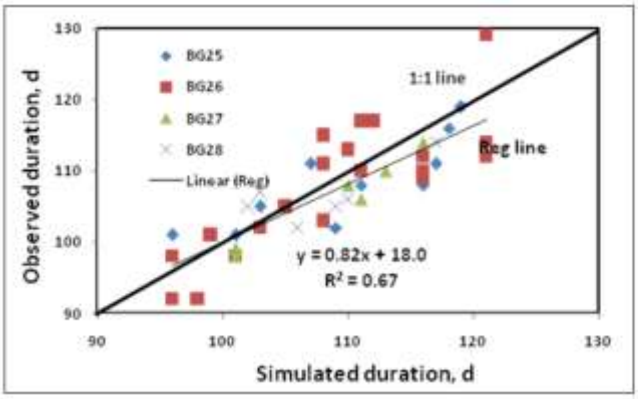

Fig-6: Observed and simulated crop duration of wheat during validation process (Dinajpur location)

Figure-7 shows simulated and observed biomass yield in different crop growth stages as the process for model's validation and performance seems to be satisfactory. Simulated biomass yield matches with observed biomass yield although simulated biomass yield is little higher than observed biomass yields. Observed biomass yield of wheat increases with the increase of crop duration and maximum biomass yield were obtained at 110 DAS.

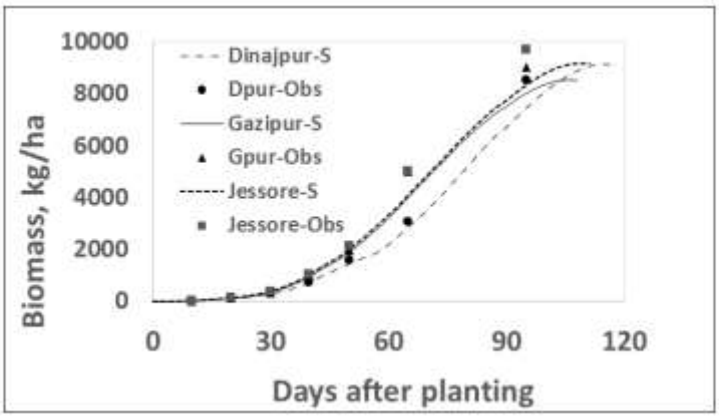

Fig-7: Observed and simulated biomass yield of wheat during validation process (three test location results)

CONCLUSION

DSSAT version 4.6 was calibrated for BARI Gom 25-28 cultivars of wheat for Bangladesh environment. This was carried out mainly through setting of the genetic coefficients for the test cultivars. After successful calibration of the model, validation was done for two wheat growing locations of Bangladesh and the performance was done through temporal course of above ground biomass, phenology and grain yield at harvest. It could be concluded that the model works well for Bangladesh growing environment, and can thus be take for application in natural resource management and climate change impact analysis studies.

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