Rice (*Oryza sativa* L.) yield gap using the CERES-rice model of climate variability for different agroclimatic zones of India

P. K. Singh[1,]*, K. K. Singh[1], L. S. Rathore[1], A. K. Baxla[1], S. C. Bhan[1], Akhilesh Gupta[2], G. B. Gohain[1], R. Balasubramanian[3], R. S. Singh[4] and R. K. Mall[4]

[1]Agromet Service Cell, India Meteorological Department, Lodhi Road, New Delhi 110 003, India
[2]Deparment of Science and Technology, New Delhi 110 016, India
[3]Agrimet Pune, New Delhi 411 005, India
[4]Banaras Hindu University, Varanasi 221 005, India

The CERES (crop estimation through resource and Environment Synthesis)-rice model incorporated in DSSAT version 4.5 was calibrated for genetic coefficients of rice cultivars by conducting field experiments during the *kharif* season at Jorhat, Kalyani, Ranchi and Bhagalpur, the results of which were used to estimate the gap in rice yield. The trend of potential yield was found to be positive and with a rate of change of 26, 36.9, 57.6 and 3.7 kg ha^{-1} year^{-1} at Jorhat, Kalyani, Ranchi and Bhagalpur districts respectively. Delayed sowing in these districts resulted in a decrease in rice yield to the tune of 35.3, 1.9, 48.6 and 17.1 kg ha^{-1} day^{-1} respectively. Finding reveals that DSSAT crop simulation model is an effective tool for decision support system. Estimation of yield gap based on the past crop data and subsequent adjustment of appropriate sowing window may help to obtain the potential yields.

Keywords: Agroclimatic zones, genetic coefficients, rice model, yield gap.

YIELD gap estimation in any crop helps to have target-oriented approach in achieving regional food security. Crop simulation models have been used to determine potential yield of many crops for which the yield gap in a given environmental situation can be determined and possibilities for yield improvement can be assessed. The estimated yields serve as a reference for calculating the required various agronomic inputs and for assessing their environmental impacts. Patel *et al.*[1,2] found that estimation of yield gap based on past data and subsequent adjustment of appropriate sowing window definitely provide possibilities for obtaining potential yields. Bell and Fischer[3] studied the potential yields of wheat in the Yaqui valley was maximum in the period 1968–90 using the CERES-wheat model. Aggarwal and Kalra[4] made a comparison of climatic potential versus actual wheat yields in New Delhi. Aggarwal *et al.*[5] calculated yield gap as the difference between the yield levels and the average measured yields of a region. The results showed that irrespective of the definition of potential yield, there was considerable yield gap across all states in all crops, indicating the scope for increasing rainfed yields in future. On an average, the gap relative to simulated rain-fed potential yield was 2560 kg ha^{-1} for rice, 1120 kg ha^{-1} for cotton and 860 kg ha^{-1} for mustard. Such a national average rainfed yield gap could not be estimated for wheat because of the large percentage of irrigated area in all the states. The mean yield gap based on the average of simulated, experimental and on-farm rainfed potential yields was 1670 kg ha^{-1} for rice, 770 kg ha^{-1} for cotton, 460 kg ha^{-1} for mustard and 70 kg ha^{-1} for wheat. It remains to be quantified if these biophysical estimates of yield gaps can be bridged economically.

Pathak *et al.*[6] studied trends of climatic potential and on-farm yield of rice and wheat in the Indo-Gangetic Plains. Due to the importance of yield gap analysis for yield improvement, an attempt has been made here to study the appraisal of rice yield gap under different agroclimatic conditions (Bihar, Jharkhand, West Bengal and Assam) of India using the CERES-rice model. The works of Wickham[7] and Ahuja[8] clearly show that the yield variation in rice crop production due to weather, management and biotic factors can be addressed through a modelling approach. Later several studies have attempted the same with different levels of success at developing an ideal weather-dependent model for rice crop.

Attachai[13] used the CERES-rice model to develop a decision-support system for fast assessment of rice-cropping alternative in lowland areas of Thailand. The system that evolved caters for decision making at the farm and policy levels; it comprises of the model validated for the area of interest and an analytical tool for answering several ‘what if’ questions. The study demonstrated that the CERES-rice model is able to simulate low yields obtained by farmers in northeastern Thailand and the relatively higher yields in northwestern Thailand. The study proved the validation of the model in finding alternative ways to improve farm performance with regard to rice production.

Rice as a staple food crop plays an important role in the Indian economy. In Punjab, it ranks second after wheat in terms of area, production and productivity. About 65% of gross cropped area in India corresponds to the summer monsoon season (about 70% of the total annual rainfall in India occurs during June to September). Rice is the most important cereal crop in India; it occupies nearly 35% of the total area under foodgrains and contributes 15–20% cropped area of rice comes under *kharif* acreage, indicating its heavy dependence on monsoon rainfall. Fluctuation in the total seasonal rainfall and intra-seasonal distribution has a strong link to rice productivity. Moisture stress due to prolonged dry spell or thermal stress due to heat-wave conditions significantly

*For correspondence. (e-mail: pksingh66@gmail.com)

affect the rice productivity when they occur in critical life stages of the crop. Similarly, wet spell promotes the spread of pests and diseases, thus leading to significant loss in crop yield unless preventive measures are adopted. Lack of our understanding of link between climate variability and crop productivity could seriously endanger sustained agricultural production in the coming decades. The average national productivity of rice is currently about 2 tonnes per hectare. In contrast, yields of about 6 tonnes per hectare have been achieved in Uttar Pradesh, Punjab and Haryana due to favourable environmental conditions and better management techniques in these states. In order to ensure a balanced growth and development in agriculture, a comprehensive understanding and assessment of the likely impact of intraseasonal and interannual variability in climate on our agricultural productivity is warranted[14].

The traditional rice-growing states of eastern India constitute Assam, Bihar, Jharkhand, Odisha, West Bengal, Chhattisgarh and eastern parts of Uttar Pradesh, which account for 61% of the total rice area and 51% of total rice production in the country. Rice is one of the main crops of Bihar, but its productivity is poor. More than 60% rice area in Bihar is located in the low-productivity zone that contributes more than 50% of rice production in the state. Area covered under rice with high-yielding varieties is about 65% and irrigation facility is available for about 40% rice area in the state. If productivity of the low-productivity zone is increased, rice production can be increased considerably without increasing the area under the crop. More than 50% of the total area under rice in the state is concentrated in the very low-productivity category, with none falling under high and medium productivity categories. Average productivity of the state is 1021 kg ha^{-1}, which is very much below the national average[14]. West Bengal ranks first with about 78% of total area under rice cultivation coming under high and medium productivity groups, accounting for nearly 84% of the total rice production in the state. Area under high-yielding varieties are nearly 85%. Triennium average productivity of the state is 2259 kg ha^{-1}, as against 1947 kg ha^{-1}, the triennium average productivity of the country[14]. Productivity of rice in Assam is poor, with more than 50% of the rice cultivated in low-productivity areas. High-yielding varieties constitute less than 45% of the area under coverage. In addition, the irrigation facility too is poor with less than 22% of area cultivated with rice being irrigated. Thus, rice productivity in Assam is far below the national average[14].

In this study, the ability of the CERES-rice crop simulation model has been established using weather data from four stations, viz. Jorhat (Assam), Kalyani (West Bengal), Ranchi (Jharkhand) and Bhagalpur (Bihar). Crop growth simulation models are useful tools for considering the complex interaction between a range of factors that effects crop performance, including weather, soil properties and crop management. The CERES-rice model simulates crop growth, development and yield. The present study focuses on the selection of suitable cultivars and appropriate time of transplanting as factors using the CERES-rice model for different agroclimatic zones.

In the present study, the CERES-rice model embedded in DSSATv4.5 was used to evaluate the potential yields of rice for 21 years (1990–2010) in Jorhat, Kalyani, Ranchi and Bhagalpur. The corresponding daily weather data (T_{max} and T_{min}, rainfall and bright sunshine) for each station were collected from India Meteorological Department (IMD), New Delhi. The district-wise rice yield data for same period were obtained from Department of Agriculture and Cooperation (DAC), Government of India and New Delhi. The soil information needed for the model was obtained from the research stations.

Soil input files include physical and chemical description of the soil profile with separate information for each horizon, soil reflection coefficient, stage-1 soil evaporation coefficient, soil water drainage constant, USDA SCS run-off curve number, thickness of soil layer, lower limit of extractable soil water for soil layer, drained upper limit of extractable soil water for layer, saturated water content for soil layer, pH for each layer of the soil profile and root distribution weighing factor for the soil. The terms 'lower limit' and 'drained upper limit' correspond to the permanent wilting point and field capacity respectively[15]. Total extractable soil water is a function of soil physical characteristics as well as rooting depth of rice crop.

Crops genetic input data, which explain how the rice cultivar responds to the environment during its life cycle, have been derived for cultivars Ranjeet, Shatabadi, Vandana and Rmansuri[16].

Genetic coefficients of ruling cultivars grown in Assam, West Bengal, Bihar and Jharkhand have been derived by taking the recent field experiments conducted at Agro-Met Field Units (AMFUs) of IMD under Forecasting Agricultural output using Space, Agrometeorology and Land base Observations scheme (FASAL) and Gramin Krishi Mausam Sewa (GKMS) project. CERES-rice model was validated for different agroclimatic zones with satisfactory performance, which has been directly used in analysing crop growth performance and yield[16].

The total yield gap was calculated using difference between the actual and potential yield of rice crop; the management gap was calculated as the difference between attainable yield and actual yield, and the sowing gap was calculated as the difference between potential yield and attainable yield.

The CERES-rice model was used to simulate three different transplanting dates (Jorhat: 15 June and 1 and 25 July; Kalyani: 1, 15 and 30 July; Ranchi: 25 June and 10 July and 25 July; Bhagalpur: 1, 15 and 30 July) and different rice cultivars (Ranjeet, Shatabadi, Rmansuri and Vandana) for the period between 1990 and 2010. The model was calibrated for genetic coefficients of rice

Table 1. Relation between rice yield and rainfall analysis for different locations in India

Station	Transplanting date	Yield (kg/ha)	Rainfall (mm)
Jorhat, Assam	15 June	2165, CV (13.4) and SD (290.2)	889, CV (20.7) and SD (183.7)
	1 July	3331.7, CV (10.9) and SD (363.9)	882.1, CV (19.4) and SD (170.8)
	25 July	2032.0, CV (14.7) and SD (298.4)	696.1, CV (20.9) and SD (145.4)
Kalyani, West Bengal	1 July	3391.8, CV (10.8) and SD (364.8)	882.7, CV (25.9) and SD (228.8)
	15 July	3885.0, CV (10.8) and SD (420.4)	818.9, CV (27.5) and SD (225.5)
	30 July	3208.0, CV (11.4) and SD (364.6)	697.6, CV (28.9) and SD (201.3)
Ranchi, Jharkhand	25 June	1592.0, CV (24.8) and SD (395.0)	805.0, CV (32.4) and SD (260.7)
	10 July	2215.9, CV (12.0) and SD (264.9)	800.8, CV (33.9) and SD (271.5)
	25 July	1271.3, CV (11.7) and SD (148.1)	691.6, CV (25.5) and SD (176.1)
Bhagalpur, Bihar	1 July	3502.6, CV 9.6) and SD (334.9)	856.6, CV (25.6) and SD (219.7)
	15 July	3697.0, CV (18.7) and SD (691.8)	777.0, CV (28.1) and SD (218.0)
	30 July	3554.0, CV (29.3) and SD (104.1)	665.0, CV (29.1) and SD (193.5)

CV, Coefficient of variation; SD, Standard deviation.

cultivars by conducting field experiments during the *kharif* season at the field sites, which were used to estimate the yield gap in rice yield. The association between simulated and observed grain yield was significant ($R^2 = 85$–94) for the cultivars. The CERES-rice model was validated for Jorhat, Kalyani, Ranchi and Bhagalpur locations. Historical actual yield rice in all four districts failed to exhibit significant trends during the study period (1990–2010).

In Jorhat district, the crop yield when rice was sown either early (15 June) or late (25 July) was less than the yield obtained when sown on 1 July (the optimum sowing date). The early yield varied from 1468 to 2739 kg ha^{-1} with an average yield of 2165 kg ha^{-1}. The standard deviation was 290.2 kg ha^{-1} and the coefficient of variation (CV) 13.4%. The average rainfall for early sowing date was 894.3 mm with a standard deviation of 183.7 mm and the coefficient of variation being 20.7%. The normal yield varied from 2468 to 3976 kg ha^{-1} with an average yield of 33,331.7 kg ha^{-1} (refs 17 and 18). The standard deviation and coefficient of variation were 363.9 kg/ha and 10.9% respectively, and the average rainfall was 882.1 mm (Table 1). The standard deviation was 170.8 mm with coefficient of variation 19.4%. The last sown yield varied from 1490 to 2635 kg ha^{-1}, with average yield 2032 kg ha^{-1}. The coefficient of variation was 14.7% with a standard deviation of 298.4 kg ha^{-1}. The average rainfall was 696.1 mm with standard deviation and coefficient variation 145.4 mm and 20.9% respectively (Table 1).

Actual yields for Jorhat district as reported by the Directorate of Agriculture ranged from 1198 kg ha^{-1} in 2006 to 2120 kg ha^{-1} in 1990, with average of 1719.9 kg ha^{-1} for the period 1990–2010 (Table 2). The standard deviation of yield was 204.5 kg ha^{-1} with CV of 12%. Pentad of actual yield varied from 1779 (1990–94) to 1614 kg ha^{-1} (2009–10), showing a slightly decreasing trend of yield (Figure 1). Pentad of 2005–10 showed decreasing trend resulting from lower yield of 1198 kg ha^{-1} in 2006 and 1379 kg ha^{-1} in 2007 due to mid-season droughts (Figure 2). Moreover, the three-year moving average of actual yield showed decreasing trend and was well supported by values for the individual years. The moving average remained more or less the same as the average yield for the districts. The data on past crop performance during several decades in some regions of the world suggest that year-to-year variation of rice growth and development was mostly due to weather changes[6]. Sinha *et al.*[19] observed that the growth and productivity of rice and wheat showed either a decline or stagnation in several intensive farming districts of Punjab and Haryana.

The potential yield was simulated using DSSAT model ranging from 3126 kg ha^{-1} in 2010 to 4111 kg ha^{-1} in 1994, with average yield of 3501.8 kg ha^{-1} (Table 2). The potential yield simulated by the model was 2.1 times higher than the actual yield at Jorhat as the yield of a crop cultivar when grown in environments to which it is adapted, with nutrients and non-limiting water supply and effective control of pest and diseases. Potential yields of wheat in India were similarly three times higher than their current actual yield levels, whereas in northwest India, this difference was smaller. The potential yield as simulated by the model for the period between 1990 and 2010 was found to be non-significant in Jorhat (Figure 1). The potential yield of rice and wheat crops have shown signs of stagnation/decline from the recent analysis of several long experiments carried out throughout Asia[20,21]. Similar results were observed for wheat by Akula[22], when simulation was carried out using WTGROWS and INFOCROP model at Anand.

For the estimation of attainable yields, various management practices play a significant role. Generally, farmers faced several constraints in various crop management practices. The optimum sowing was simulated using DSSAT model and analyses of the trend and mean yield. The attainable yield ranged from 2210 kg ha^{-1} (2009) to 3410 kg ha^{-1} (2004) with an average yield of 2795 kg ha^{-1} (Table 2). The standard deviation of yield was 421 kg ha^{-1} with CV of 15%. Model-simulated attainable yield for delayed sowing of rice by 20 days

Table 2. Estimation of rice yield gap by CERES-rice model in different agroclimatic zones of India

	Yield (kg ha^{-1})			Yield gap (kg ha^{-1})		
Parameters	Actual	Potential	Attainable	Total	Management	Sowing
Jorhat						
Mean	1719.9	3501.8	2795.4	1782.0	1075.6	706.4
SD	204.5	272.3	421.9	362.0	471.1	227.7
CV%	12	8	15	20	44	32
Slope	–8.65	26.31	–36.98	–17.67	–28.33	10.67
Kalyani						
Mean	2471	3956	3927	1486	1456	29
SD	236.1	332.8	357.6	307.5	312.3	54.8
CV	9.6	8.4	9.1	20.7	21.4	186.7
Slope	5.58	36.97	33.17	5.4	0.23	3.79
Ranchi						
Mean	1368.2	2506.9	1777.3	1138.7	409.1	729.6
SD	515.0	575.1	483.8	512.7	270.7	475.4
CV	37.6	22.9	27.2	45.0	66.2	65.2
Slope	64.99	57.58	55.96	–12.39	–9.03	4.2
Mean	1159.0	5527.1	5270.0	4368.1	4060.2	257.1
Bhagalpur						
SD	294.5	238.6	140.9	393.6	359.8	161.8
CV	25.4	4.3	2.7	9.0	8.9	62.9
Slope	–5.95	3.69	6.7	9.64	19.72	–3.01

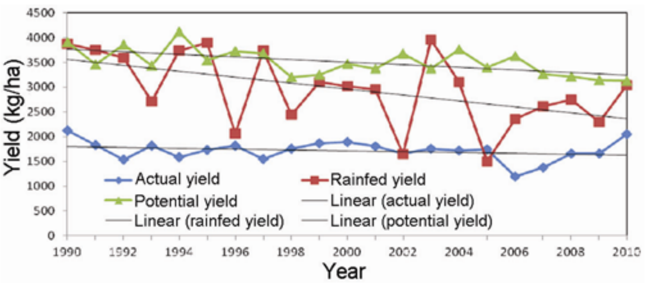

Figure 1. Simulated yield (kg/ha) from 1990 to 2010 at Jorhat, Assam.

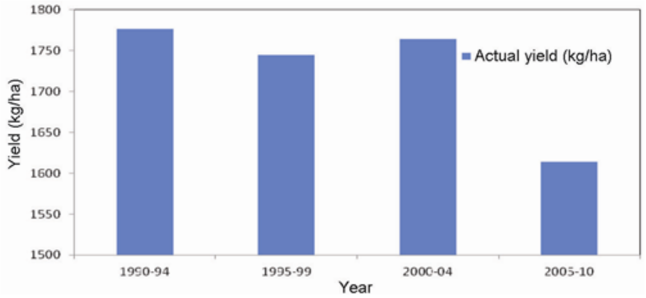

Figure 2. Pentad actual yield (kg/ha) from 1990 to 2010 at Jorhat, Assam.

ranged from 1533 kg ha^{-1} in 2010 to 2243 kg ha^{-1} in 1992 with average yield of 1892 kg ha^{-1}. The standard deviation was 197.6 kg/ha, with CV being 10%.

The average total yield gap (potential – actual yield) estimated by the CERES-rice model was 1782 kg ha^{-1} ranging from 1081 kg ha^{-1} in 2010 to 2529 kg ha^{-1} in 1994. The standard deviation was 362 with CV of 20%. The linear trend of total yield gap indicated a rate of change of 89 kg ha^{-1} day^{-1} (Figure 3), indicating a decreasing trend. Mall and Srivastava[23] have reported decline in total yield gap in wheat crop in their study at Varanasi, Uttar Pradesh.

Management gap can be defined as the yield gap between attainable yield and actual yield. The management gap simulated by the model ranged from 243 kg ha^{-1} in 2010 to 1762 kg ha^{-1} in 1992 with average yield 1075.6 kg ha^{-1} (Figure 3 and Table 2). The standard deviation was 471.1 kg ha^{-1}, with a CV of 44%. The high CV value indicates the variability in weather. The management gap was found non-significant and showed a decreasing trend, clearly suggesting the poor and untimely management followed by the farmers (Figure 3).

Sowing gap can be defined as the difference between potential and attainable yields due to a delay in sowing by 20 days. The sowing gap varied from 335 kg ha^{-1} in 1996 to 1069 kg ha^{-1} in 2001 (Figure 3). The average sowing gap yield was estimated to be 706.4 kg ha^{-1} with a CV and standard deviation of 22% and 228 kg ha^{-1} respectively (Table 2). The high CV value indicates the variability in weather and temperature, which are the major influencing factors in rice production. The estimated sowing yield gap was recorded to be 35 kg ha^{-1} day^{-1} by the model (Figure 3). Patel *et al.*[2] have reported wheat yield gap of 18 kg ha^{-1} day^{-1}, whereas Aggarwal and Kalra[4] have quantified a wheat yield gap of 50 kg ha^{-1} day^{-1} to be delayed sowing.

In Kalyani district the early (1 July) and late sown dates (30 July) of rice yield crop is less than optimum sowing date (15 July). The early yield varied from 2204 to 3872 kg ha^{-1} with an average yield of 3391.8 kg ha^{-1}. The standard deviation was 364.8 kg ha^{-1} with a coefficient of variation 10.8%. The average rainfall of early sown yield was 882.7 mm with standard deviation and coefficient of variation 228.8 mm and 25.9% (Table 1). The normal sown yield varied from 3251 to 5305 kg ha^{-1} with an average yield of 3885.3 kg ha^{-1}. The standard deviation and coefficient of variation were 420.4 kg ha^{-1} and 10.8% respectively, and the average rainfall was 818.9 mm with standard deviation of 225.5 mm and a coefficient of variation 27.5% (Table 2). The last sown yield varied from 2025 to 3868 kg ha^{-1} with an average yield of 3208 kg ha^{-1}. The coefficient of variation was 11.4% with a standard deviation of 364.6 kg ha^{-1}. The average rain-fall was 697.6 mm with the standard deviation and coefficient of variation being 201.3 mm and 28.9% respectively (Table 1).

The actual yields of Kalyani district as reported by the Directorate of Agriculture ranged from 1746 kg ha^{-1} in 2010 to 2889 in 2009 kg ha^{-1} with an average of 2471 kg ha^{-1} between 1990 and 2010 (Table 2). The standard deviation of the yield was 236.1 kg ha^{-1} with a CV of 9.6%. Pentad of actual yield varied from 2360 (1995–99) to 2538 kg ha^{-1} (2000–04), showing an increasing trend of yield. Pentad of 1995–99 showed a decreasing trend resulting from lower yield (Figure 4). Moreover, the three-year moving average of actual yield showed an increasing trend and was well supported by the values for the individual years (Figure 5). The moving average remained more or less the same as the average yield of the districts. The data on past crop performance for several decades in some regions of the world suggest that year-to-year variation of rice growth and development was mostly due to weather changes[6]. Sinha *et al.*[19] observed that the growth and productivity of rice and wheat showed either a decline or stagnation in several intensive farming districts of Punjab and Haryana.

The potential yield was estimated using CERES-rice model that ranged from 3401 kg ha^{-1} in 1992 to 5305 kg ha^{-1} in 2010, with an average yield of 2507 kg ha^{-1} (Table 2). The potential yield estimated by the model was 1.6 times higher than the actual yield of Kalyani, as the yield of the crop cultivar Shatabadi when grown in non-stress condition. The potential yield compared with simulated by the model for the period 1990–2010 and was found to be significant at Kalyani, however the increasing rate of changes (Figure 5).

The optimum sowing was estimated using CERES-rice model, and the trend and mean yield of the crop was analysed (Figure 5). The attainable yield ranged from 3391 kg ha^{-1} in 1992 to 5037 kg ha^{-1} in 2010 with an average yield of 4022 kg ha^{-1}. The standard deviation of yield was 374.6 kg ha^{-1} with a CV of 9.2% (Table 2). The attainable yield for 20 days delayed sowing of rice simulated through the model ranged from 3306 kg ha^{-1} in 2010 to 5006 kg ha^{-1} in 2004 with an average yield of 4011 kg ha^{-1}. The standard deviation was 486.0 kg ha^{-1} with a CV of 12.1%.

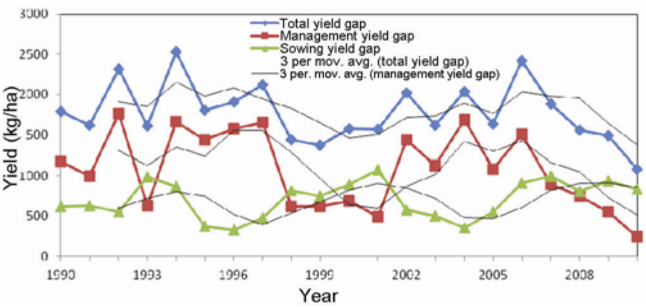

Figure 3. Yield gap in the rice production level from 1990 to 2010 at Jorhat, Assam.

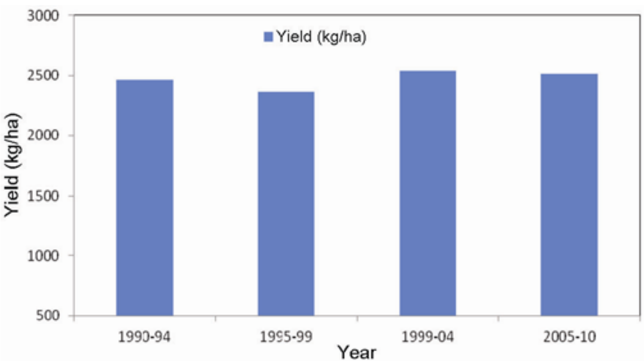

Figure 4. Pentad actual yield (kg/ha) from 1990 to 2010 at Kalyani, West Bengal.

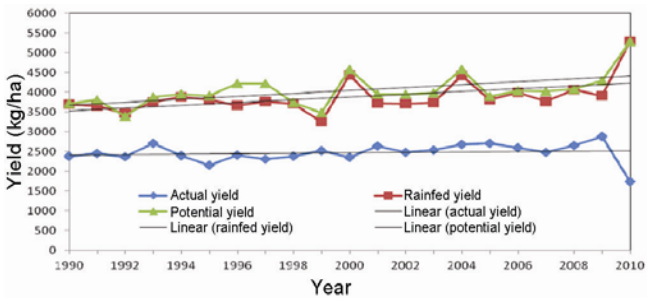

Figure 5. Simulated yield (kg/ha) from 1990 to 2010 at Kalyani, West Bengal.

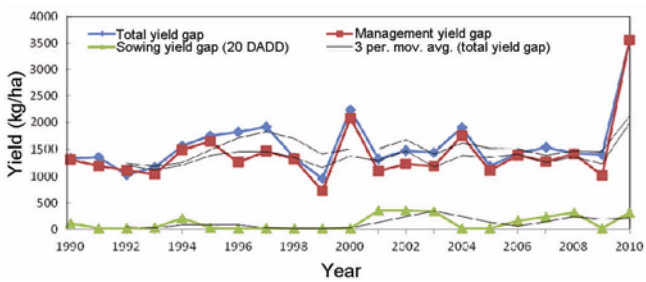

Figure 6. Yield gap in the rice production from 1990 to 2010 at Kalyani, West Bengal.

The average total yield gap was 1581 kg ha^{-1}, ranging from 952 kg ha^{-1} in 1999 to 3535 kg ha^{-1} in 2010 (Figure 6). The standard deviation was 543.0 kg ha^{-1} with a CV of 34.3% (Table 2). The linear trend of total yield gap indicated a rate of change of 5.4 kg ha^{-1} day^{-1}, but it was found statistically non-significant (Figure 6). However, it showed an increasing trend. Mall and Srivastava[23] have reported decline in total yield gap in wheat crop at Varanasi.

The management gap ranged from 720 kg ha^{-1} in 1999 to 3559 kg ha^{-1} in 2010 with an average yield 1415 kg ha^{-1} (Figure 6). The standard deviation was 569 kg ha^{-1} with a CV of 40.2% (Table 2). The higher CV value indicated the variability in weather and temperature, the major influencing factors in rice production. The management gap was found to be non-significant showed as it a decreasing trend at a rate of 67.4 kg ha^{-1} $year^{-1}$, clearly suggesting good management practice followed by the farmers (Figure 6).

The sowing gap varied from 9 to 244 kg ha^{-1} in 2007 and 2010 respectively (Figure 6). The average sowing gap yield was estimated to be 29 kg ha^{-1} with a CV and standard deviation of 54.8% and 186.7 kg ha^{-1} respectively (Table 2). The estimated sowing yield gap was recorded as 2 kg ha^{-1} day^{-1} by the model (Figure 6).

In Ranchi district, the early (25 June) and late sown (25 July) rice crop yield was less than the yield from optimum sowing date rice crop (10 July). The early rice crop yield varied from 1105 to 2434 kg ha^{-1} with an average yield of 1592 kg ha^{-1}. The standard deviation was 395.2 kg ha^{-1} with a coefficient of variation of 24.8%. The average rainfall of early sown rice crop was 805.0 mm with a standard deviation and coefficient of variation of 260.7 mm and 32.4% respectively (Table 1). The normal sown yield varied from 1534 to 2655 kg ha^{-1} with an average yield of 2215.9 kg ha^{-1} (Table 1). The standard deviation and coefficient of variation were 264.9 kg ha^{-1} and 12.0% respectively, and was with the average rainfall of 800.8 mm. The standard deviation was 271.5 mm and the coefficient of variation 33.9%. The last sown yield varied from 919 to 1761 kg ha^{-1} with an average yield of 1271.3 kg ha^{-1} (refs 17 and 18). The coefficient of variation was 11.7% with a standard deviation of 148.1 kg/ha. The average rainfall was 691.6 mm with standard deviation and coefficient of variation of 176.1 mm and 25.5% respectively (Table 1).

The actual yields of Ranchi district as reported by the Directorate of Agriculture ranged from 628 kg ha^{-1} in 1992 to 2830 kg ha^{-1} in 2008 with an average of 1368 kg ha^{-1} for the period 1990–2010 (Figure 7). The standard deviation of yield was 515.0 kg ha^{-1} with a CV of 37.6%. Pentad of actual yield varied from 877 kg ha^{-1} (1990–94) to 1935 kg ha^{-1} (2005–10), showing an increasing trend in yield (Figure 8). Pentad of 1990–2004 showed decreasing trend resulting from lower crop yields during 1993 (628 kg ha^{-1}) and 1992 (674 kg ha^{-1}). Moreover, the three year moving average of actual yield showed an increasing trend and was well supported by values for the individual years (Figure 8). The moving average almost remains more or less same as the average yield for district yields. The data on past crop performance for several decades in some regions of the world suggests that year-to-year variation of rice growth and development was mostly due to abrupt variation of meteorological parameters.

The potential yield was estimated using CERES-rice model for crop yield ranging from 1427 kg ha^{-1} in 1992 to 3276 kg ha^{-1} in 2002 with an average yield of 2507 kg ha^{-1} (Table 2). The potential yield estimated by the model was 1.9 times higher than the actual yield of Ranchi. Potential yields of wheat in India were similarly three times higher than their current actual yield levels, whereas in northwest India this difference was smaller. The potential yield as simulated by the model between 1990 and 2010 was found to be significant at Ranchi (Figure 7).

The optimum sowing was estimated using DSSAT model, and the trend and mean yield were analysed. The attainable yield ranged from 1139 kg ha^{-1} in 1992 to 2947 kg ha^{-1} in 2008 with an average yield of 1773 kg ha^{-1} (Table 2). The linear trend was found to be 56 kg ha^{-1} $year^{-1}$ and non-significant (Figure 7). The standard deviation of yield was 483.8 kg ha^{-1} with a CV of 27.2%. Attainable yield simulated by the model for 20 days of delayed sowing of rice, ranged from 1147 kg ha^{-1} in 2009 to 2495 kg ha^{-1} in 1995 with an average yield 1352 kg ha^{-1}.

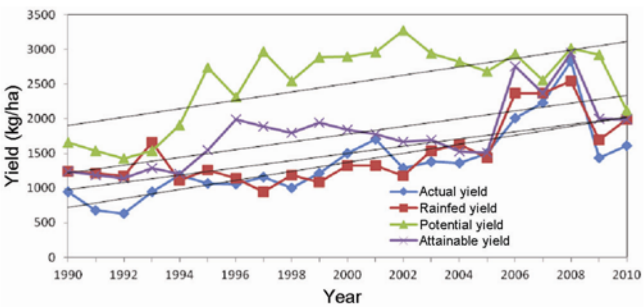

Figure 7. Simulated yield (kg/ha) from 1990 to 2010 at Ranchi, Jharkhand.

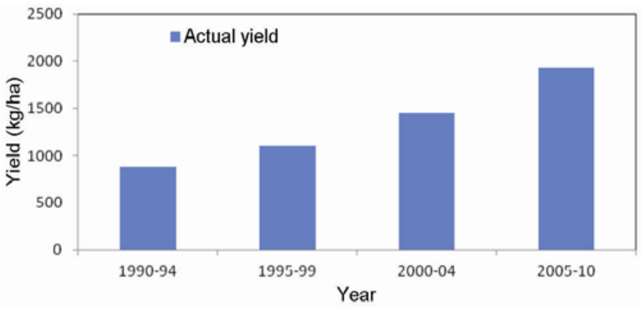

Figure 8. Pentad actual yield (kg/ha) from 1990 to 2010 at Ranchi, Jharkhand.

The standard deviation was 305.4 kg ha^{-1} with a CV of 22.6%.

The average total yield gap estimated by the CERES-rice model was 1138.7 kg ha^{-1}, ranging from 188 kg ha^{-1} in 2008 to 1983 kg ha^{-1} in 2002 (Figure 9). The standard deviation was 512.7 kg ha^{-1} with a CV of 45% (Table 2). The linear trend of the total yield gap indicated a rate of change of 74 kg ha^{-1} day^{-1} to be non-significant (Figure 9), but showing a decreasing trend.

The management gap simulated by the model ranged from 10 kg ha^{-1} in 2005 to 937 kg ha^{-1} in 1996 with average yield 409.1 kg ha^{-1} (Figure 9). The standard deviation was 271 kg ha^{-1} with a CV of 66.2% (Table 2). The higher CV value indicates the variability in weather and temperature and the major influencing factors in rice production. The management gap was found non-significant and showed a decreasing trend at the rate of – 9 kg ha^{-1} $year^{-1}$ (Figure 9), clearly suggesting good management practices followed by the farmers.

The sowing gap varied from 91 kg ha^{-1} in 1996 to 230 kg ha^{-1} in 2004 (Figure 9). The average sowing gap yield was estimated as 149 kg ha^{-1} with a CV and standard deviation of 27.2% and 41 kg ha^{-1} respectively (Table 2). The estimated sowing yield gap was recorded as 49 kg ha^{-1} day^{-1} by the model (Figure 9). Patel and Shekh[1] have estimated wheat yield gap of 95 kg ha^{-1} day^{-1} in delayed sowing. Patel *et al.*[2] has estimated yield gap of 18 kg ha^{-1} day^{-1} in delay sowing crop yield. Aggarwal *et al.*[4] have quantified a wheat yield gap of 50 kg ha^{-1} day^{-1} for delay sowing.

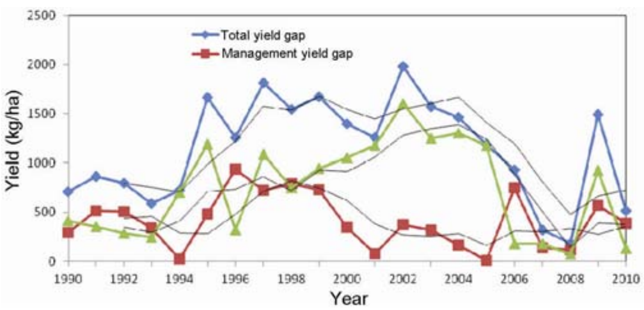

Figure 9. Yield gap in the rice production from 1990–2010 at Ranchi, Jharkhand.

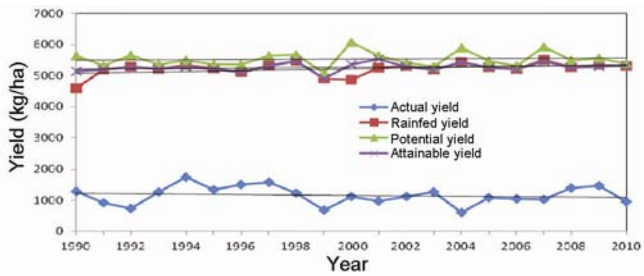

Figure 10. Simulated yield (kg/ha) from 1990 to 2010 at Bhagalpur, Bihar.

In Bhagalpur district, the yield of early (1 July) and late sown (30 July) rice crop was less than the yield obtained by the optimum sowing date (15 July). The early yield varied from 2539 to 3974 kg ha^{-1} with average yield of 3502.6 kg ha^{-1}. The standard deviation was 334.9 kg ha^{-1} with a coefficient of variation of 9.6% (Table 1). The average rainfall of early sown crop yield was 856.6 mm with a standard deviation and coefficient of variation 219.7 mm and 25.6% respectively (Table 1). The normal sown yield of the crop varied from 2721 to 4257 kg ha^{-1} with an average yield of 3917 kg ha^{-1}. The standard deviation and coefficient of variation were 299.5 kg ha^{-1} and 7.6% respectively, and average rainfall was 777.0 mm. The standard deviation was 218.0 mm with a coefficient of variation of 28.1% (Table 1). The late sown yield varied from 3527 kg ha^{-1} to 3934 kg ha^{-1} with an average yield of 3681 kg ha^{-1} (refs 17 and 18). The coefficient of variation was 2.8% with a standard deviation of 102.4 kg ha^{-1}. The average rainfall was 665.0 mm with a standard deviation and coefficient of variation of 193.5 mm and 29.1% respectively (Table 1).

Actual yields of Bhagalpur district as reported by the Directorate of Agriculture ranged from 607 kg ha^{-1} in 2004 to 1740 kg ha^{-1} in 1994 with average of 1159 kg ha^{-1} for the period 1990–2010 (Table 2 and Figure 10). The standard deviation of yield was 294.5 kg ha^{-1} with a CV of 25.4% (Table 2). Pentad of actual yield varied from 1266 (1995–1999) to 1018 kg ha^{-1} (2000–2004), showing slight increasing trend of yield (Figure 11). Pentad of 2000–2004 showed a decreasing trend as a result of lower yields during 607 kg ha^{-1} in 2004 and 979 kg ha^{-1} (Figure 11). The moving average remained almost the same as the average yield for all the districts.

The potential yield was estimated using CERES-rice model and it ranged from 5078 kg ha^{-1} in 1999 to 6076 kg ha^{-1} in 2000 with an average yield of 5527 kg ha^{-1} (Figure 10). The potential yield estimated by the model was 4.6 times higher than actual yield of Bhagalpur, as a result of the crop cultivar Rajender Mansuri being grown in environments to which it is adapted with nutrients, non-limiting water supply and effective control of pests and diseases. Potential yields of wheat in India too were similarly three times higher than their current actual yield levels, whereas in northwest India this difference was smaller. The potential yield was simulated by the model for the period 1990–2010 and was found to be non-significant at Bhagalpur, however, with a increasing rate of change of 4 kg ha^{-1} $year^{-1}$.

The optimum sowing date, and the trend and mean yield were analysed using DSSAT model. The attainable yield ranged from 4910 kg ha^{-1} in 1999 to 5519 kg ha^{-1} in 2001 with an average yield of 5270 kg ha^{-1} (Table 2). The standard deviation of yield was 140 kg ha^{-1} with a CV of 2.7%. Model simulated attainable yield for delayed sowing by 20 days for rice ranged from 3414 kg ha^{-1} in 1999 to 5375 kg ha^{-1} in 2001 with an average yield of

4603 kg ha^{-1}. The standard deviation was 403 kg ha^{-1} with a CV of 8.8%.

The average total yield gap (potential – actual yield) estimated by the CERES-rice model was 4368 kg ha^{-1}, ranging from 3753 kg ha^{-1} in 1994 to 5293 kg ha^{-1} in 2004 (Figure 12). The standard deviation was 393.6 kg ha^{-1} with a CV of 9% (Table 2). The linear trend of total yield gap indicated a rate of change of 218 kg ha^{-1} day^{-1} which was non-significant; however, the trend showed an increase (Figure 12).

The management gap simulated by the model ranged from 3315 (1990) to 4826 kg ha^{-1} (2004) with an average yield of 4064 kg ha^{-1} (Figure 12). The standard deviation was 808.6 kg/ha with a CV of 20.6% (Table 2). The management gap was found to be non-significant, but indicated an increasing trend at a rate of 13 kg ha^{-1} $year^{-1}$ (Figure 12).

The sowing gap varied from 10 kg ha^{-1} (2010) to 1474 kg ha^{-1} (2000). The average sowing gap yield was estimated to be 318.9 kg ha^{-1} with CV and standard deviation of 93.8% and 299.1 kg ha^{-1} respectively (Table 2). The high CV value indicates the variability in weather and temperature. The quantified estimated sowing yield gap was recorded to be 17 kg ha^{-1} day^{-1} by the model (Figure 12). Patel *et al.*[2] in their study have reported a wheat yield gap of 18 kg ha^{-1} day^{-1}. Aggarwal *et al.*[4] in their study have quantified wheat yield gap of 50 kg ha^{-1} day^{-1} when sowing is delayed.

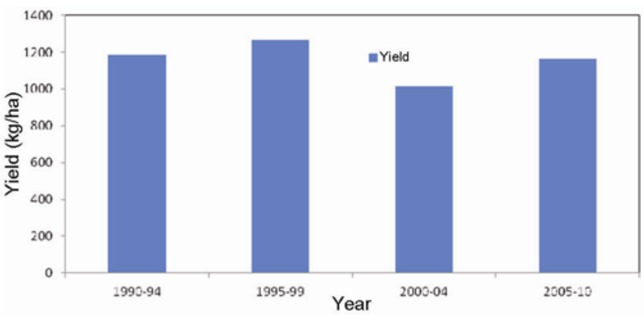

Figure 11. Pentad actual yield (kg/ha) from 1990 to 2010 at Bhagalpur, Bihar.

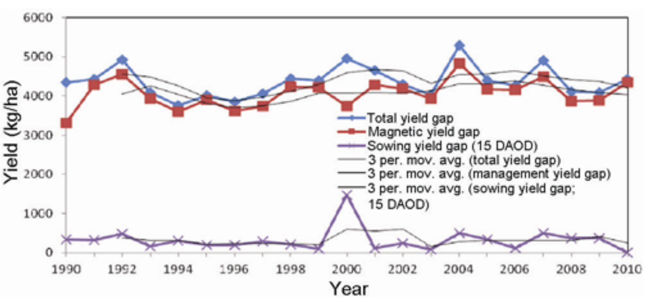

Figure 12. Yield gap in the rice production level from 1990 to 2010 at Bhagalpur, Bihar.

The CERES-rice model was used for the estimation of optimum date of sowing/transplanting of *kharif* rice crop when the farmer management practices at field and climate conditions are most favourable for maximum possible crop yield. Five transplanting dates were taken during the period 15 June to 25 July at Jorhat district, 1 to 30 July at Bhagalpur district, 1 to 30 July at Kalyani district and 25 June to 25 July at Ranchi district[17,18]. It has been shown that 1 July (Jorhat district), 15 July (Bhagalpur district), 15 July (Kalyani district) and 10 July (Ranchi district) are optimum dates of sowing/transplanting as they give maximum average possible potential and attainable yield without any constraint of management practices (Table 1). The result shows considerable decrease trend in rice yield when there is delay of 20 days or more than the optimum sowing/transplanting date (Table 1). This is because weather and climatic conditions are not favourable for good production of rice.

Results of the phenology simulation of the model show that they are accurate enough at flowering stage to take broad scale planning of cultural operations in the field as well as tactical decision-making at farm level, notwithstanding the higher accuracy requirement for maturity date simulation for decision making regarding time of harvest. The early and late sown is compare to optimum sown rice. The higher accuracy of the grain yield predication shows the ability of the model to simulate crop growth in climatic conditions of the Gangetic plain zone under rainfed condition. In this context, it may be noted that the yield prediction of rice crop is crucial for the economic planning in the different states. From Table 1 it is clear that there is considerable gap between the productivity potential and actual yield. This suggests that there is a great scope for increasing the rice yields with suitable technological intervention like selection of suitable variety, quality seed, optimum sowing/planting time, optimum inputs by quantity and time of application, etc. The biomass production and its partitioning efficiency are important to assess the effect of drought or stress.

From Table 2 it is clear that there is considerable gap between the productivity potential and actual yields. This suggests that there is great scope for increasing the rice yield with suitable technological interventions like selection of suitable variety, quality seed, optimum sowing/planting time, optimum inputs by quantity and time of application. The biomass production and its partitioning efficiency are important to assess the effect of drought or stress.

The CERES-rice model is able to simulate rice yields which are in fair agreement with the currently reported yields at the selected sites. The model is also able to simulate the year-to-year variation in rice yield, showing its wide range applicability in diverse environmental conditions for agricultural decision-making. Excessive rain conditions due to temporal variation in rainfall (associated with observed swings in the continuity of monsoon) during the cropping season are found to adversely affect crop development and growth at critical life stages and the yields at the selected sites (even under irrigated conditions). Early transplanting date seems to provide higher average yields at all locations, whereas late transplanting is found to adversely affect rice yield in Assam, West Bengal, Jharkhand and Bihar.

The reduction in yield due to delay in sowing was 706.4, 29, 729.6 and 257.1 kg ha^{-1} at Jorhat, Kalyani, Ranchi and Bhagalpur districts respectively. This shows that one day delay in sowing decreases rice yield to the tune of 35.3, 1.9, 48.6 and 17.1 kg ha^{-1} day^{-1} at Jorhat, Kalyani, Ranchi and Bhagalpur districts respectively. Sowing time is a non-monitory input. If properly managed, it can result in yield improvement.

However, there are some limitations while using the crop models. The simulation outputs are only valid at a point or small farm. The model does not represent spatial features because of large variabilities in soil, rainfall and management conditions. Other assumptions include presence of soil nutrients in adequate supply preventing stress on crop. Similarly, loss of yield due to weed, pests and diseases is not included in the model. The rise in surface temperature, particularly during the humid monsoon season, may create more conductive conditions for pest infestation and hence lead to loss of crops. These aspects are not yet explicitly treated in most of the crop simulation models.

1. Patel, H. R. and Shekh, A. M., Yield gap and trend analysis of wheat using CERES-wheat model in three districts of Gujarat state. *J. Agrometeorol.*, 2006, **8**(1), 28–39.
2. Patel, V. J., Patel, H. R. and Pandey, V., Estimation of wheat yield gap in Anand and Panchmahal districts using CERES-wheat model. *J. Agrometeorology.* (*Spec. Issue-part-2*), 2008, 393–397.
3. Bell, M. A. and Fischer, R. A., Using yield predication to assess yield grains: a case study for wheat. *Field Crops Res.*, 1994, **36**, 161–166.
4. Aggarwal, P. K. and Kalra, N., Analysing the limitation set by climatic factors, genotype and water and nitrogen availability on productivity of wheat II. Climatic potential yield and management strategies. *Field Crops Res.*, 1994, **38**, 93–103.
5. Aggarwal, P. K., Hebbar, K. B., Venugopalan, M. V., Rani, S., Bala, A., Biswal, A. and Wani, S. P., Quantification of yield gaps in rain-fed rice, wheat, cotton and mustard in India. Global theme on agro ecosystems, report no. 43 and page 36, ICRISAT, Hyderabad, 2008.
6. Pathak, H. *et al.*, Trend of climatic potential and on-farm yield of rice and wheat in the Indo-Gangetic Plains. *Field Crops Res.*, 2003, **80**, 223–234.
7. Wickham, T. H., Predicting yield in lowland rice through a water balance model in Philippine irrigation systems: research and operations. International Rice Research Institute (IRRI), Los Banos, Philippines, 1973, pp. 155–181.
8. Ahuja, S. P., Computer simulation of primary production of semiaquatic system using rice (*Oryza sativa*). Analysis and modeling of the physics of biological–climatological coupling. Ph D thesis, University of California, Devis, 1974.
9. Angus, J. F. and Zandstra, H. G., Climatic factors and the modeling of rice growth and yield. In *Agrometeorology of the Rice Crop*, IRRI, Los Banos, Philippines, 1979, pp. 189–199.
10. Kropff, M. J., Van Laar, H. H. and Mathews, R. B. (eds), ORYZA1, an ecophysiological model for irrigated rice production. In SARP Research Proceedings, AB-DLO and TPE-WAU, Wageningen and IRRI, Los Banos, 1994, p. 110.
11. Penning de Vries, F. W. T., Jnasen, D. M., Ten Berge, H. F. M. and Bakema, A. H., *Simulation of Ecophysiological Processes of Growth of Several Annual Crops*, PUDOC, Wageningen, 1989, p. 271.
12. Whisler, F. D., Sensitivity test of the crop variables in RICEMOD, IRRI, Res., Pap. Ser., 1983, pp. 89–103.
13. Attachai, J., A decision support system for rapid assessment of low land rice-based alternative in Thailand. *Agric. Syst.*, 1995, **47**, 245–258.
14. Diwakar, M. C. (ed.), *Rice in India during 10th Plan*, Directorate of Rice Development, Patna, 2009.
15. Ritchie, J. T., Wheat phasic development, In *Modelling Plant and Soil System* (eds Hanks, J. and Ritchie, J. T.), Agron. Mongr., ASA, CSSA, Madison, WI, USA, 1991, p. 31.
16. Singh, K. K., Baxla, A. K., Singh, P. K. and Balasubramanian, R., A report on database for rice cultivars used in CERES-rice crop simulation model in different agroclimatic zones of India, Agromet Service Cell, New Delhi, 2010.
17. Singh, P. K., Singh, K. K., Baxla, A. K., Rathore, L. S., Kumar, B., Balasubramanian, R. and Tyagi, B. S., Crop yield prediction using CERES-rice model for the climate variability of South Bihar alluvial zone of Bihar (India). AP Chapter of Association of Agrometeorologists National Symposium on Agro Meteorology, at Central Research Institute for Dry land Agriculture (CRIDA), Hyderabad, 2013, pp. 22–23.
18. Singh, P. K., Singh, K. K., Baxla, A. K. and Rathore, L. S., Impact of climatic variability on Rice productivity using CERES-rice models Eastern plain zone of Uttar Pradesh. In Third International Agronomy Congress on 'Agriculture Diversification, Climate Change Management and Livelihoods', IARI, New Delhi, 26–30 November 2012 and extended summaries vol. (2), 2012, pp. 236–237.
19. Sinha, S. K., Singh, G. B. and Rai, M., *Decline in Crop Productivity in Harayana and Punjab: Myth or Reality?* Indian Council of Agricultural Research, New Delhi, 1998, p. 89.
20. Bhandari, A. L., Ladha, J. K., Pathak, H., Padre, A. T., Dawe, D. and Gupta, R. K., Trend of yield and soil nutrient status in long-term rice–wheat experiment in the Indo-Gangetic Plains of India. *Soil Sci. Soc. Am. J.*, 2002, **66**, 162–170.
21. Yadav, R. L., Diwivedi, B. S., Orsad, K., Tomar, O. K., Shurapali, N. J. and Pandey, P. S., Yield trends and changes in soil organic-C and available NPK in a long-term rice–wheat system under integrated use of manures and fertilizers. *Field Crops Res.*, 2000, **68**, 219–246.
22. Akula, B., Estimating wheat yields in Gujarat using WTGROWS and INFOCROP models. Ph D thesis, Anand Agriculture University, Sardar Krishinagar, Anand, Gujarat, India, 2003.
23. Mall, R. K. and Srivastava, M. K., Prediction of potential and attainable yield of wheat: a case study on yield gap. *Mausam*, 2002, **53**, 45–52.

Received 13 August 2013; revised accepted 22 August 2015

doi: 10.18520/cs/v110/i3/405-413