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Yield, evapotranspiration and water productivity of rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) system in Punjab (India) as influenced by transplanting date of rice and weather parameters

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ABSTRACT

Rice–wheat cropping system being highly productive and profitable, dominates the irrigated alluvial tract of Indo-Gangetic Plain of South Asia. In this region, the transplanting is staggered over a longer period (starting from early May to end of June) due to scarcity of migratory labour and power supply. Yield response of rice to different transplanting dates gets varied with weather conditions at different growth stages of the crop as well as with the occurrence of insect-pests infestation. The present investigation, therefore, concerns the effects of different dates of transplanting and weather parameters on yield, evapotranspiration and water productivity of rice and subsequent wheat in rice–wheat cropping system in Indian Punjab involving field experimentation for 2 years and simulation for 23 years. For the simulation study, crop production and management (CROPMAN) model which is a multi-year, multi-crop and daily time step cropping system was used. The simulated rice yields with varying dates of transplanting of rice complimented the field results and showed an increasing trend when transplanting was shifted from high to low evaporative demand owing to favourable weather conditions for plant growth. Duration of temperature greater than 37 °C during post-transplanted seedling period (Ds_T), temperature greater than 33 °C (T_F) and number of rain showers (NS_F) from flowering to pollen stage (75–90 days after transplanting) affected rice yield (Y_r) significantly. Sixty-seven percent variability in rice yield was explained by these weather parameters following the equation $Y_r = 0.656SR - 36.9Ds_T - 175.9T_F - 102.5NS_F + 11995$. Shifting of transplanting dates also resulted into a saving of 192 mm as wet (evapotranspiration) and 590 mm as dry (irrigation) water. Real and apparent crop water productivities (grain yield per unit of water consumed by the crop as ET and irrigation water applied, respectively) were more (>70%) in rice transplanted under lower (end of June onwards) than higher evaporative demand (mid May).

1. Introduction

In the Indian Punjab, rice (*Oryza sativa* L.) is grown on 2.61 m ha during *kharif* and wheat (*Triticum aestivum* L.) on 3.41 m ha during *rabi* out of the total 5.04 m ha geographic area. It contributes 40% of the state gross domestic product (GDP) and 50% of food grains to the central pool. The state average productivity of rice and wheat are 5.5 and 4.2 t ha^{-1},

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respectively. In the central districts of the Punjab, rice–wheat is a major cropping system. Most of the operations, from transplanting to harvesting are performed by the migrated labourers from other states. In the early eighties, rice was generally transplanted in the month of June (mid to late). However, in the present days with the persistent increase in area under rice (1.18 m ha in 1981 and 2.6 m ha in 2005) coupled with the shortage of migratory labourers and power supply during the peak periods of transplanting have compelled the farmers to transplant rice at earlier dates (even in mid May). Transplanting in the month of May coincides with the supra optimal maximum temperature 39–42 °C (2–5 °C more than the optimum temperature of 37 °C for rice) and a high potential evapotranspiration of 12 mm day^{-1}. Therefore, in the month of May, crop requires frequent irrigations for establishment of seedlings under such extreme weather conditions. This advancement in date of transplanting has increased the irrigation water requirement of the crop to 1800–2400 mm, mostly met through ground water exploitation in order to meet the higher ET demand (750 mm). As a result, ground water is depleting at an alarming rate (0.4–0.9 m per year). Presently, almost 80% geographical area of Punjab falls under dark categories (where ground water withdrawal is more than 85% of the total water recharge). To save water, shifting of transplanting date of rice from relatively higher (May) to lower (late June) evaporative demand is being advocated. However, results from some experiments showed inconsistent trends in yields (Singh et al., 1996, 2001; Arora, 2006) with shifting of the transplanting date from high to low evaporative demand without assigning any scientific reasons. Farmers also have common perception that with postponing the date of transplanting (from mid May to June end onwards), rice yield may decline. To understand the reasons for this inconsistent behaviour of yields, there is a need to have information on weather parameters and their response to yield over a longer periods, as the crop response varies from year-to-year depending upon the dynamic weather conditions. Traditional method of field experimentation may not give conclusive results. Under such circumstances, pre-validated crop growth models can immensely help in determining the appropriate cause of inconsistency in yield, if any. The crop growth models also help in understanding the crop management practices in varying climate and soil conditions and are also economic in terms of both money and time (Matthews et al., 2002). Crop production and management (CROPMAN) is one such model, which is a multi-year, multi-crop and daily time step cropping system model. It can be used to simulate rice yield under different dates of transplanting as well as post-rice wheat yields in rice–wheat cropping system. For Punjab conditions, the CROPMAN model has already been customized. Recently, Jalota et al. (2006a,b) have applied it successfully for assessing the yield response of chickpeas in rice–chickpea system and cotton and wheat in cotton–wheat system to irrigation water, soil texture and precipitation. The present study aimed at: (i) to calibrate and validate the CROPMAN model for rice–wheat system, (ii) its application to simulate crop yield, evapotranspiration and water productivity in rice–wheat system under varying dates of transplanting of rice and (iii) to understand the effect of weather parameters on rice yield.

2. Materials and methodology

2.1. Experimentation

An experiment on rice–wheat cropping system was conducted during the years 2004 and 2005 on loamy sand soil at the Research Farm, Punjab Agricultural University (PAU), Ludhiana (30°56′N, 75°52′E and 247 m m.s.l), in India. Soil physical (texture, bulk density and hydraulic conductivity) and chemical (electrical conductivity (EC), soil reaction (pH), soil organic carbon (SOC) and ammonical and nitrate nitrogen) properties of experimental field were determined up to a depth of 1.8 m at an interval of 0.15 m following the standard procedures. The sand, silt and clay contents were determined by International Pipette, bulk density with core and hydraulic conductivity with constant head methods (Jalota et al., 1998). EC was measured with solu-bridge (Chopra and Kanwar, 1976), pH with potentiometric (Jackson, 1973) and SOC by wet digestion methods (Walkley and Black, 1934). Ammonical and nitrate nitrogen were determined by KCl method (Keeney, 1982). Daily weather data on maximum and minimum temperature, mean relative humidity, wind speed and rainfall during the crop growth period were obtained from Meteorological Laboratory at Punjab Agricultural University. The treatments included three dates of transplanting, viz. May 26 (D_1), June 10 (D_2) and June 25 (D_3). Irrigations comprised of continuous flooding for 15 days after transplanting followed by intermittent irrigation at 4 days interval up to 14 days before harvest. Total 3 treatments in 12 plots of size 6.5 m × 4 m were quadruplicated in a randomised block design. Seedlings of 30 days old nursery of variety PR118 were transplanted on three dates of transplanting with a spacing of 20 cm between row to row and 15 cm between hill to hill on two times puddled soil. Puddling was done by running cultivator in the standing water (75 mm) followed by planking. At each date of transplanting, 40 kg N and 30 kg P_2O_5 and 30 kg K_2O per hectare were applied at the time of transplanting. Second and third (40 kg ha^{-1} each) and an additional dose of N (30 kg ha^{-1}) were applied at 22, 43 and 70 days after transplanting in D_1, D_2 and D_3 dates, respectively. To control weeds (*Phalaris minor* L.), butachlor 50 EC 3000 ml ha^{-1} was applied 2 days after transplanting. Monocrotophos (1400 ml ha^{-1}), Chloropyriphos (2.5 l ha^{-1}), Padan (18 kg ha^{-1}), Indofill-45 (1250 g ha^{-1}) and Tilt 25 EC (500 ml ha^{-1}) were used periodically to control insect-pests and diseases. Irrigation water at each application was measured with the parshal flume. The irrigation was stopped 15 days prior to harvesting (Table 3). At harvest of the crop, rice yield was measured at 14% grain moisture content.

After the harvest of paddy, the field was irrigated with 100 mm of water as pre-sowing irrigation and was prepared by tilling the land for wheat crop with a disc and spring-tyne harrow followed by leveling. The wheat crop was sown with seed drill on November 11 with row to row spacing 22.5 cm. The seed rate was 100 kg ha^{-1}. A uniform application of 26.2 kg of P as single super-phosphate and 50 kg of K as muriate of potash ha^{-1} were drilled at the time of seeding (basal). Fertilizer N at a uniform rate (120 kg ha^{-1}) was applied in 2 equal splits; half at seeding (basal) and the remainder 30 days after sowing (with first irrigation). The wheat crop was harvested in the third week of April.

2.2. CROPMAN model

A number of simulation models are available for studying the response of individual crops to management practices. Since the crops growing in a system have influence on each other, there is a need to simulate the cropping system as a whole. CROPMAN is a window based, multi-year, multi-crop, daily time step cropping system simulation model and contains the EPIC crop/environmental simulation model as an engine. In this model, there is a provision to define cropping system as unique combination of the rotation (crop order), as well as the type, timing, rate and method for each operation associated with the rotation. This model has a huge data base on tillage equipments, fertilizers, pesticides and crop and soil parameters. The user can modify the cropping system and management using the management editor module. The equations describing the relationships between rainfall, evapotranspiration, runoff, erosion and production are described in a document by Williams et al. (1990). The CROPMAN model can be used to determine the effect of management strategies on agricultural production and soil and water resources. The major components in the model are weather, hydrology, erosion–sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics and plant environment control. The input data required for the model are weather, soil, crop and management practices data. The weather data includes solar radiation, maximum and minimum temperatures, mean relative humidity, rain and wind speed. The soil data comprises of soil bulk density, wilting point, field capacity, sand, silt, organic nitrogen, pH, sum of bases, organic matter, $CaCO_3$, CEC, initial NO_3 concentration, phosphorous, phosphorous sorption rate and saturated hydraulic conductivity (Table 1). The crop data requires biomass energy ratio, biomass energy decline rate, fraction of root weight at emergence, fraction of root weight at maturity, heat units required for germination, LAI decline factor, lower limit of harvest index, maximum crop height, maximum LAI, maximum root depth, maximum stomatal conductance, minimum temperature for plant growth, optimum temperature for plant growth, vapour pressure deficit, threshold vapour pressure deficit, vapour pressure deficit value and harvest index (Table 2). This model also provides the user with the post-simulation analysis for comparing the results obtained under varying soil types and management practices.

Table 1 – Important properties of the soils used as input in the CROPMAN model

Parameters	Value
Bulk density of soil layer ($Mg\,m^{-3}$)	1.50
Wilting pointing ($mm\,mm^{-1}$)	0.08
Field capacity ($mm\,mm^{-1}$)	0.24
Sand (%)	71.00
Silt (%)	12.00
Clay (%)	17.00
Organic nitrogen ($mg\,kg^{-1}$)	215.00
pH	8.10
EC ($dS\,m^{-1}$)	0.18
Organic matter (%)	0.24
CEC ($Cmol\,kg^{-1}$)	5.50
Initial NO_3 concentration ($mg\,kg^{-1}$)	2.00
Phosphorous ($mg\,kg^{-1}$)	8.00
Saturated hydraulic conductivity ($mm\,h^{-1}$)	25.20

2.3. Model calibration, validation and application

The crop management and production model CROPMAN was used to simulate crop yield and evapotranspiration for rice–wheat system. The soil used was Tulewal sandy loam. Important soil physico-chemical properties have been given in Table 1. Seed rate, harvest index, yield moisture content, maximum leaf area index, plant height and rooting depth data were obtained from earlier field experiments conducted at PAU research farm and rest were taken as default values (Williams et al., 1990) as given in Table 2.

The model was calibrated by making the adjustments within the permissible range (given in the model) so that the simulated crop yield matched the experimentally observed/reported yield (Mahindra, 2004). The calibrated model was validated for the year of 2004 taking the experimental dates of transplanting. After validation, the model was applied with varying dates of transplanting ranged from May 1 to July 1,

Table 2 – Plant growth parameters used as input in the CROPMAN model

Serial number	Parameters	Rice	Wheat
Experimental			
1	Seed rate ($kg\,ha^{-1}$)	60.00	100.00
2	Harvest index	0.50	0.45
3	Yield (fraction of water in yield)	0.14	0.05
4	Maximum LAI	6.00	5.00
5	Maximum crop height (m)	0.80	1.00
6	Maximum root depth (m)	0.90	1.80
Adjusted default			
7	Biomass energy ratio	35.00	30.00
8	Biomass energy decline rate	0.50	1.00
9	Fraction of root weight at emergence	0.40	0.40
10	Fraction of root weight at maturity	0.20	0.20
11	Heat units required for germination	100	100
12	LAI decline factor	0.50	1.00
13	Lower limit of harvest index	0.25	0.21
14	Maximum stomatal conductance	0.01	0.01
15	Minimum temperature for plant growth (°C)	10.00	0
16	Optimum temperature for plant growth (°C)	25	15
17	Vapour pressure deficit to WA	5.00	6.00
18	Threshold vapour pressure deficit (k Pa)	0.50	0.50
19	Vapour pressure deficit value (k Pa)	4.75	4.75

commonly practiced by the farmers in the studied region. For application of the model, crop budget representing the crop management information on field preparation operations, fertilizer application (amount and time), irrigation scheduling, pesticide application (amount and time) and harvesting date for rice–wheat cropping system were prepared as given in package of practices of Punjab Agricultural University, Ludhiana (Mahindra, 2004) (Table 3). The irrigation water used for rice transplanted on May 1, May 16, June 1, June 16 and July 1 was 2575, 2385, 2125, 1985 and 1845 mm, respectively, and 400 mm for wheat. Dates and amount of irrigation water are given in the crop budget (Table 3). The effect of five dates of transplanting, viz. May 1, May 16, June 1, June 16 and July 1 were simulated for 23 years (1982–2004) in rice–wheat rotation. The average annual rainfall for 23 years (1982–2004) was 787 $\pm$ 260 mm. The probabilities of rainfall for the range of 0–100, 100–200 and 200–300 mm during wheat crop were 0.33, 0.44 and 0.23, respectively, while for rice transplanted on normal date (June 11) these were 0.05, 0.16, 0.31, 0.27, 0.05 and 0.16 for the range of 100–200, 200–400, 400–600, 600–800, 800–1000 and 1000–1200 mm, respectively. The rice equivalent yield of rice–wheat system was calculated as:

$$\text{Rice equivalent yield} = \text{wheat grain yield} \times \left(\frac{\text{MSP of wheat}}{\text{MSP of rice}}\right) + \text{rice grain yield}$$

Here, MSP is the minimum support price (Indian Rs. 6.2 and 5.8 for wheat and rice grain kg^{-1}, respectively). Real crop water productivity (RCWP) and apparent crop water productivity (ACWP) were calculated as grain yield of individual crop and in the system per unit of water consumed by the plant as evapotranspiration and amount of irrigation water applied, respectively (Jalota et al., 2006b).

3. Results and discussion

3.1. *Observed field results*

The rice yield under D_1, D_2 and D_3 treatments were 6.6, 7.1 and 7.2 t ha^{-1} in 2004 while in 2005 it was 6.1, 6.0 and 6.0 t ha^{-1},

Table 3 – Details of the management file for rice and wheat crops (transplanted on May 16) in rice–wheat cropping system

Year	Month	Day	Operation	Equipment	Source	Amount/rate	Depth
Rice							
1	5	11	Plow	Berm maker			
1	5	13	Irrigation	Flood		75 mm	
1	5	15	Plow	Puddler			
1	5	16	Cultivator	Planker			
1	5	16	Transplanting	Transplanter			
1	5	16	Fertilizer	Hand	Urea (46-0-0)	42.0 kg ha^{-1}	10 mm
1	5	17	Spray	Hand	Basagran	3.00 l ha^{-1}	
1	5	17–31	Irrigation (daily basis)	Flood		75.00 mm	
1	6	3	Irrigation	Flood		60.00 mm	
1	6	6	Fertilizer	Hand	Urea (46-0-0)	42.0 kg ha^{-1}	10 mm
1	6	6–24	Irrigation (at 3 days interval)	Flood		60.00 mm	
1	6	26	Fertilizer	Hand	Urea (46-0-0)	42.0 kg ha^{-1}	10 mm
1	6	27	Irrigation	Flood		60.00 mm	
1	6	30	Irrigation	Flood		60.00 mm	
1	7	4–28	Irrigation (at 4 days interval)	Flood		60.00 mm	
1	8	1–29	Irrigation (at 4 days interval)	Flood		60.00 mm	
1	9	3	Irrigation	Flood		60.00 mm	
1	9	25	Harvest				
1	9	25	Kill				
Wheat							
0	10	30	Plow	Berm maker			
0	11	1	Disking	Offset			
0	11	5	Disking	Offset			
0	11	6	Plow	Cultivator			
0	11	6	Plow	Cultivator			
0	11	6	Plow	Planker			
0	11	7	Sowing	Grain drill			
0	11	11	Fertilizer	Hand	18-46-0	130.0 kg ha^{-1}	10 mm
0	11	11	Fertilizer	Hand	Urea (46-0-0)	78.0 kg ha^{-1}	10 mm
0	12	9	Irrigation	Flood		75 mm	
0	12	10	Spray	Hand	2,4-D	0.63 kg ha^{-1}	
0	12	13	Fertilizer	Hand	Urea (46-0-0)	130.0 kg ha^{-1}	10 mm
1	1	26	Irrigation	Flood		75 mm	
1	3	5	Irrigation	Flood		75 mm	
1	3	25	Irrigation	Flood		75 mm	
1	4	15	Harvest	Combine			
1	4	15	Kill				

respectively. Though the rice yields were statistically non-significant, yet it showed an increasing trend with late transplanting during 2004. The observed meteorological data indicate that the total rainfall during crop growth periods in D_1, D_2 and D_3 treatments was 314, 329 and 293 mm in the year 2004, whereas in 2005, the respective amounts were 610, 609 and 620 mm. The rainfall in the year 2004 was 50% less than that in 2005. Therefore, the effect of dates of transplanting on grain yield was not observed in the year 2005 unlike 2004. In D_1, D_2 and D_3 treatments, cumulative pan evaporation were 702, 665 and 588 mm during 2004 and 785, 651 and 527 mm during 2005, respectively. The total amount of irrigation water applied was 2470, 2410, 2320 mm during 2004 and 2420, 2260, 2090 mm during 2005, respectively. These values are on the higher side than those reported by Singh et al. (1996), as in the present study, the crop variety was of longer duration and the soil was relatively coarser in texture.

3.2. *Model validation*

The performance of the model was evaluated with respect to simulation of grain yield in variable transplanting dates. The validation of the model was performed based on the results from field experiments for the years 2004 and 2005. The comparison of simulated and observed grain yield at 14% moisture was comparable. The simulated yield of rice averaged over the three dates of transplanting and 2 years was 6.5 ± 0.3 t ha^{-1} compared to observed yield of 6.5 ± 0.6 t ha^{-1}. The linear regression between simulated and observed values forced to zero intercept gave slope 0.99 with higher coefficient of correlation (0.78) as shown in Fig. 1. The root mean square error (RMSE) was 0.38 t ha^{-1} and normalized RMSE was 5.9% of the measured yield. The validation of the model for wheat crop has already been done and described elsewhere (Jalota et al., 2006b).

3.3. *Simulation analysis*

3.3.1. *Grain yields*

The model was used to simulate rice yield in relation to date of transplanting and the carry over effect on wheat yield using weather data of Ludhiana for last 23 years (from 1982 to 2004). Simulated rice yield varied with transplanting dates (Table 4). The mean rice yields simulated for May 1, May 16, June 1, June 16 and July 1 were 5.7, 6.0, 6.3, 6.8 and 7.4 t ha^{-1}, respectively. These trends are in line with the observed experimental results during 2004, which also showed an increasing trend with the late transplanting of rice. This reaffirms the earlier

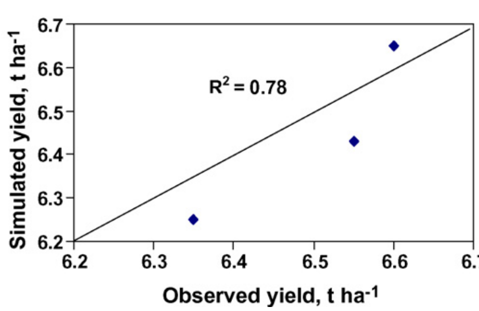

Fig. 1 – Comparison of observed and simulated rice yields.

simulated results based on CERES–rice model that the optimum date of transplanting for rice is June 15 (Hundal et al., 1999). However, the results from pooled data of 5 years reported by Singh et al. (1996) are at variance. It was postulated that inconsistency in rice yields with shifting of transplanting date might be because of either variable weather parameters or attack of insect-pests and may be due to both. De Datta (1981) reported that yield of rice may decrease with late transplanting due to limited solar radiation, probably because of the use of photosensitive variety. In this region the solar radiation (average of 23 years) during the crop season remained more than 2500 MJ m^{-2} for the rice transplanted up to June 10. It became 2400 MJ m^{-2} for July 1 transplantation. Since PR118 is photoinsensitive and long duration (155 day from seed to seed) variety, the possibility of the effect of limited radiation on yield performance in late transplanted rice is ruled out. Limited radiation may affect the yield in photosensitive and short duration varieties especially at 3–4 weeks before heading, when the mutual shading by the fully developed leaves is maximum (Stansel, 1967). The other possible weather parameters like duration of super optimal temperature during crop growth; temperature and rain during flowering to anthesis period may also affect the yield. The simulated results indicate that the frequency of days with temperature greater than upper limit of optimum (37 °C) remained for shorter period in the late transplanted rice. It was 50, 40, 24 and 6 days when the date of transplanting of rice was May 1, May 16, June 1 and June 16, respectively. However, in July 1 transplanted rice, temperature remained lesser than upper limit of optimum (37 °C) but greater than the lower limit (21 °C) during the whole growing period (Fig. 2). The relationship developed from the simulation studies between rice yield and number of days with greater than 37 °C and other weather parameters (Eq. (1)) indicated that with each such day, 37 kg rice yield is reduced. Similarly, a simulation study by Kropff et al. (1993) showed that rice yields decreased by 9% for each 1 °C increase in seasonal average temperature. Exposures of larger duration of the temperature greater than 37 °C and vapour pressure deficit during the period of plant growth will certainly decrease photoassimilation per unit of water consumed and increase respiration due to higher day temperature. Yamada (1961) reported that grain production depends on the balance between photosynthesis and respiration. In rice, the temperature coefficient of respiration (Q_{10}) is double than that of photosynthesis. Absorption of inorganic nutrients is also restricted when temperature of water is more than 36 °C (Matsubayashi, 1965). The other weather parameters affecting rice yield may be temperature (affecting germination of pollens) and rainfall (damaging or washing of pollens) during flowering to anthesis period. Maximum temperature required for germination of pollens is 33–34 °C (Grist, 1986). Supporting these findings, the results of the present simulation study also showed that rice yield remained marginally affected when the temperature is within 30–34 °C but decreased drastically with the rise in temperature up to 37 °C (Fig. 3). Severe effects of high temperature are most striking when heat stress occurs during anthesis in rice. Heat stress at anthesis prevents anther dehiscence and shedding of pollens, reduces pollination and grain number (Mackill et al., 1982; Zheng and Mackill, 1982). These results are consistent

Table 4 – Yield, evapotranspiration and crop water productivity of rice, wheat and rice–wheat system

Date of transplanting	Yield[a] ($kg\ ha^{-1}$)			Evapotranspiration (mm)			Real crop water productivity ($kg\ m^{-3}$)			Apparent crop water productivity ($kg\ m^{-3}$)		
	Range	Mean	S.D.	Range	Mean	S.D.	Range	Mean	S.D.	Range	Mean	S.D.
Rice												
May 1	4740–7080	5745	621	569–969	728	78	0.505–0.991	0.796	0.104	0.151–0.211	0.182	0.019
May 16	5030–6880	5977	529	550–770	687	54	0.661–1.042	0.874	0.084	0.167–0.246	0.200	0.020
June 1	5550–7250	6305	483	497–724	633	53	0.766–1.150	1.001	1.087	0.200–0.292	0.232	0.025
June 16	5930–7710	6780	523	480–683	593	46	0.879–1.333	1.148	0.098	0.219–0.319	0.265	0.031
July 1	6420–9010	7428	611	448–636	536	44	1.012–1.664	1.392	0.141	0.255–0.369	0.310	0.035
Wheat												
May 1	4670–5920	5290	341	369–472	427	25	1.077–1.456	1.243	0.109	0.905–1.244	1.039	0.084
May 16	4540–5430	4990	249	368–472	426	25	1.034–1.364	1.175	0.091	0.847–1.154	0.982	0.085
June 1	4470–5240	4847	199	369–473	427	25	1.014–1.319	1.140	0.081	0.802–1.112	0.954	0.088
June 16	4390–5210	4837	199	372–478	427	28	1.002–1.299	1.136	0.085	0.802–1.114	0.952	0.091
July 1	4670–5920	4295	341	333–437	399	25	0.924–1.238	1.078	0.074	0.670–1.042	0.846	0.094
Rice–wheat system												
May 1	11248–12324	11701	340	978–1415	1153	94	0.797–1.157	1.021	0.081	0.284–0.351	0.318	0.018
May 16	11008–12144	11599	373	959–1214	1111	71	0.907–1.172	1.048	0.068	0.291–0.373	0.331	0.023
June 1	11191–12574	11763	435	906–1169	1057	68	0.963–1.263	1.116	0.72	0.320–0.424	0.363	0.029
June 16	11464–13083	12225	461	878–1132	1018	87	1.035–1.348	1.204	0.081	0.343–0.452	0.396	0.033
July 1	11228–16534	12287	614	838–1072	934	57	1.096–1.459	1.318	0.080	0.365–0.477	0.421	0.038

[a] Yield for rice–wheat system is rice equivalent yield.

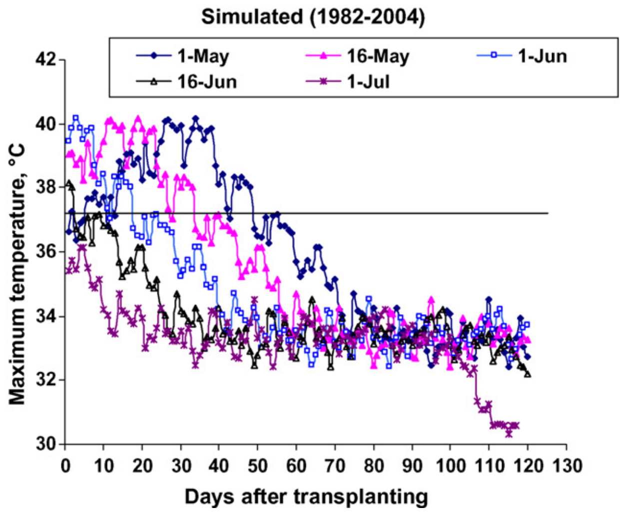

Fig. 2 – Time trend of maximum temperature in rice growing period as influenced by date of transplanting.

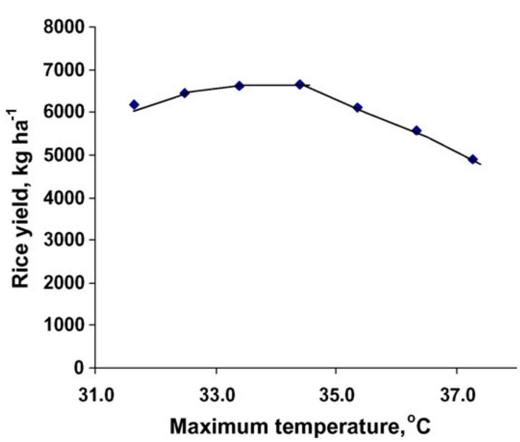

Fig. 3 – Rice yield response to maximum temperature from flowering to anthesis period (75–90 days).

with a number of previous studies showing the sensitivity of flowering in rice to high temperature. These studies have revealed that when temperature at anthesis is greater than 31 °C, there is a sharp decline in fertile or filled spikelets. The reduction of filled spikelets decreased the panicle biomass and harvest index (Satake and Yoshida, 1978; Yoshida et al., 1981; Matusi et al., 1997; Ziska et al., 1997). Recently, Kobata and Uemuki (2004) reported that high temperature during grain filling period of rice enhance the grain dry matter increase rate, but this enhancement in dry matter increase is insufficient to completely compensate for the concomitant reduced grain filling period and as a result, grain yield decreases. In addition to temperature, yield also may be affected by the probability of occurrence of rain as the rain damages/washes away the pollens during flowering to anthesis period and thus affects pollination and fertilization. As a result more number of sterile spikelets will be produced. In the simulation study, the number of showers was 7, 7, 7, 1 and 0 with rice transplanted on May 1, May 16, June 1, June 16 and July 1, respectively (Table 5). The effects of these parameters on rice yield were quantified by fitting a multiple regression equation with 67% variability.

$$Y_r = 0.656S_R - 36.9Ds_T - 175.9T_F - 102.5NS_F + 11995 \quad (R^2 = 0.67),\ n = 115 \tag{1}$$

where Y_r is the rice yield in kg ha^{-1}, T_F the temperature in degree centigrade, NS_F the number of rain showers from flowering to anthesis period, Ds_T the number of days with temperature greater than 37 °C, S_R the solar radiation in MJ m^{-2}, R^2 the coefficient of determination and n is the number of observations. This equation predicted higher yields with late transplanted rice similar to as was observed in the experiment. The equation also explained that weather conditions, viz. longer duration of temperature greater than 37 °C during growing season, temperature greater than 33 °C and more number of rain showers from flowering to anthesis period decreased the yield of rice. If the magnitudes of all these weather parameters are in optimal range and still, there is a decrease in yield with late transplanting, it will be definitely due to secondary outbreak of insect-pests developed on the earlier transplanted rice in the vicinity. In the present experimentation, no decrease in yield was observed with shifting of transplanting date because the crop was kept free from attack of insect-pests by intense spraying of the pesticides.

In post-rice wheat, the simulated mean yield following rice transplanted on May 1, May 16, June 1, June 16 and July 1 were 5290, 4990, 4847, 4837 and 4295 kg ha^{-1}, respectively (Table 4). The simulated rice equivalent yield in rice–wheat system was also influenced by shifting the date of transplanting of rice. In rice–wheat system, rice equivalent yield was more in late transplanted rice although subsequent wheat yield was adversely affected. This may be ascribed to the reason that with late transplanting, the magnitude of rate of increase in rice yield was much higher to the corresponding rate of decrease in post-rice wheat yield. As a consequence, the rice

Table 5 – Mode values of weather parameters at Ludhaina

Date of transplanting	Days of temperature >37 °C	Temperature from flowering to anthesis period	Number of showers from flowering to anthesis period
May 1	48	32.1	7
May 16	39	34.0	7
June 1	24	34.0	7
June 16	9	33.9	1
July 1	1	32.0	0

yield could able to compensate the loss in subsequent wheat yield and thereby, increased the rice equivalent yield with late transplantation. Apart from variation in yield due to treatments of transplanting dates, yield also varied substantially year-to-year due to climatic factors.

3.3.2. *Evapotranspiration*

The mean simulated evapotranspiration (ET) representing water demand by the crop varied from 728 to 536 mm for rice transplanted between May 1 and July 1 (Table 4). The decreased water demand with late transplanting was associated with lower potential evapotranspiration demand by the atmosphere. With shifting the date of transplanting of rice from May 1 to May 16, June 1, June 16 and July 1, there was a reduction of ET by 6, 13, 19 and 26%, respectively. Arora (2006) and Singh et al. (1996) also reported lower ET in late transplanted compared to the earlier or normal transplanted rice. The range depicting year-to-year variation in ET was 400, 220, 217, 203 and 188 mm for May 1, May 16, June 1, June 16 and July 1 dates of transplanting, respectively. Higher variation in earlier transplanted rice is due to erratic nature of pre-monsoon rains. Evapotranspiration in wheat grown after different dates of transplanting of rice did not differ except for sown following July 1 transplanted rice, in which ET demand was 28 mm lesser than the wheat sown following earlier transplanted rice. In rice–wheat system as a whole, water demand was decreased with shifting the transplanting of rice from higher to lower evaporative demand. Total water demand for the system was decreased by 4, 8, 12 and 19% in May 16, June 1, June 16 and July 1, respectively, compared to May 1 transplanted rice.

3.3.3. *Crop water productivity*

Real crop water productivity of rice as an individual crop and of rice–wheat system was more in the late compared to earlier transplanted rice (Table 4). This was due to more yields and lesser ET in the late compared to the earlier transplanted rice. However, the values of RCWP compared to apparent crop water productivity were more in rice and comparable in wheat. This may be ascribed to reason that in rice more irrigation water was applied to make the soil conditions favourable for plant growth, while in wheat lesser irrigations were required. In wheat sown after late transplanted rice, RCWP was lesser due to lesser yields compared to the wheat sown after earlier transplanted rice. However, the values of RCWP compared to ACWP were 4.3-, 1.2- and 3.1-folds higher in rice, wheat and rice–wheat system, respectively. This may be due to the reason that rice grown under high evaporative demand required more irrigation water, while wheat grown under low evaporative demand required less.

3.3.4. *Weather analysis*

The statistical analysis (mode values) of long-term weather data (1982–2005) at Ludhiana given in Table 5 showed that rice transplanted on June 16 onward has lesser number of rain showers (one), suitable temperature for pollen germination (32.5 °C) and sufficient solar radiation (763 MJ m^{-2}) during flowering to anthesis period in addition to optimum temperature (<37 °C) throughout the crop growth period, which favors rice productivity.

4. Conclusions

Both field and simulated studies indicate that transplanting of rice in mid June onwards has favourable weather conditions for rice production in Indian Punjab. The yield of rice is significantly influenced by temperature throughout the crop growth period and was more pronounced from flowering to anthesis period. Besides temperature, the number of showers during this period also affects the yield. With the shifting of transplanting dates of rice from higher (mid May) to lower (end of June onwards) evaporative demand, there is an increase in grain yield of rice while there is a reduction in evapotranspiration and irrigation water applied. As a consequence, both the real and apparent crop water productivities are enhanced in rice as well as in rice–wheat system too. The critical analysis of long-term weather reveals that weather conditions are favourable for growth and production in late transplanted rice under Indian Punjab and if there is any reduction in yield, it will be due to factors other than the weather.

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