Chapter-13

Crop Management Options to Optimise Land and Water Productivity in the Rice-Wheat System in NW India

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Abstract

Irrigation water scarcity is major threat to sustainability of the rice-wheat system in north-west India, which is critical to the food security of India. There are many crop management practices which can help to reduce irrigation water requirement for rice and wheat. A simulation study was conducted using the validated APSIM model to evaluate various crop management practices for rice and wheat, and for rice-wheat cropping system as whole, for their impacts on irrigation water requirement, yield and water productivity. Management options evaluated were wheat and rice sowing/transplanting dates, rice irrigation water management, and rice residue management. The results suggested that optimum sowing date for wheat in north-west India is late October to early November in terms of maximising yield, WP_I and WP_{ET}. Yield decreased by around 60 kg $ha^{-1}d^{-1}$ (1% d^{-1}) when sowing was delayed from 10 November to 30 December. Mulching often resulted in higher yields advantage, more so with earlier (23 October) sowings, and the yield advantage decreased at 4% per day beyond 23 October. For rice, the optimum transplanting date for reducing irrigation water requirement was mid June (11 and 21 June), due to lower evaporative demand and higher crop season rainfall than for other transplanting dates. The most effective practice for reducing irrigation input was by changing rice irrigation management from continuous flooding to AWD. There was no yield penalty when changing from continuous flooding to irrigation up to 4 days after the pond water had disappeared (4-d). There was about 25% and 50% irrigation water reduction by switching from continuous flooding to 2-d and 4-d irrigation scheduling, respectively, with a significant increase in irrigation water productivity (WP_I). The irrigation water saving was due to reduced deep drainage. Wheat yields were not significantly different under mulch and non-mulched conditions under different rice irrigation schedules. However, mulched wheat following frequently irrigated rice (CF, 2-d, 4-d) required lower irrigation input than non-mulched wheat following rice with the same rice irrigation schedules. There was no effect of mulching on irrigation input to wheat following rice with less frequent rice irrigation (7-d, 10-d and 15-d). On average, there was a gradual increase in wheat irrigation input with delay in rice irrigation frequency from CF to 15-d. WP_{ET} and WP_I were higher with mulch within each rice irrigation schedule. Total system (rice+wheat) yield and water productivity trends were similar to those for rice irrigation schedules and not greatly affected by rice residue management in the wheat crop.

Introduction

Rice-wheat cropping systems are of great importance for food security in India, and for the livelihoods of hundreds of millions of rural poor. Occupying approximately 10 Mha, the rice-wheat systems of India provide 52% of the total national calorie intake (FAO, 2007). The highly mechanised, irrigated rice-wheat systems of north-west (NW) India are particularly important for food security. The two small states of Punjab and Haryana occupy less than 3% of the total geographical area of India but contribute about 54% of the rice and 84% of the wheat procured by the Government of India (Yadvinder-Singh et al., 2003). The productivity of rice-wheat systems needs to increase to keep up with population growth in India, which is predicted to increase from 1.12 billion in 2008 to 1.35 billion by 2025 (UNESCO, 1995). However, the sustainability of these systems is threatened by soil degradation, declining water availability and environmental degradation, as a result of high cropping intensity with imbalanced nutrient input, high irrigation input, intensive tillage, and almost complete residue removal.

More than 90% of the rice-wheat area of Punjab and Haryana is irrigated using groundwater (Ambast et al., 2006). This part of India has access to the world's largest underground aquifer system, containing 4,800 km^3 of water (Tanwar and Kruseman, 1985). There are currently around 1.3 million tubewells pumping groundwater for agriculture in Punjab, and 0.7 million tubewells in Haryana (Hira 2009, Statistical abstract for Haryana). As a result, 97% and 83% of the cultivable area of Punjab and Haryana, respectively, is under irrigation, in comparison with an average of 39.5% for India as a whole. The rapid increase in groundwater extraction and increased cropping intensity resulted in a steady decline in the depth to the groundwater in the NW India (Ambast et al., 2006; Hira, 2009; Rodell et al., 2009). The decline in the water table has accelerated alarmingly in some areas in the recent years; for example, in parts of Ludhiana district in central Punjab, the rate of groundwater decline increased from about 0.2 m $year^{-1}$ during 1973 to 2001 to about 1 m $year^{-1}$ during 2000 to 2006.

There are many improved crop water management technologies which can help to reduce the irrigation requirement by reducing losses through deep drainage, seepage, runoff and soil evaporation (Humphreys et al., 2010 and Sudhir-Yadav et al., 2012). These crop management technologies include date of transplanting for rice, irrigation scheduling for rice and wheat, mulching, crop establishment/tillage methods, variety duration, and laser levelling. These crop and land management practices have been tested in field experimentation for their irrigation water saving potential but the results are variable from year to year and across locations (Humphreys et al., 2010). In almost all studies management practices were evaluated for individual rice or wheat crop yield and irrigation water productivity, however these crops are grown in rotations with carry over effects on soil conditions, especially water and nutrient availability, and on the window of oppurtunity for field operations for succeeding crops. For example transplanting time of rice and rice varietal duration will determine whether the succeeding wheat crop can be sown at the optimum time. So to evaluate the impact of crop technologies on water use and productivity, these practices should also be tested for the cropping system as a whole rather than for individual crops. However, it is not possible to evaluate the many combinations of management practices for rice and wheat in field experimentation due to time and resource limitations. However a validated cropping system model can be a helpful tool to evaluate the potential of these management practices on a system basis. In the present study we used the APSIM farming system model to evaluate the different crop management practices for rice and wheat, and for the rice-wheat system, in terms of yield, irrigation water use and water productivity.

Material and methods

All simulations were conducted using 40 years (1970-2010) of weather data from the meteorological station at Punjab Agricultural University (PAU), Ludhiana, on a sandy loam soil. The soil parameters were based on the properties of a field site at PAU, Ludhiana (Timsina et al., 2008; Yadvinder-Singh et al., 2009). The soil had a plant available water capacity (PAWC) of 110 mm over the 0-60 cm soil profile, and a PAWC of 290 mm over the 0-180 cm soil profile. The stage 1 soil evaporation parameter (U) was set to 10 mm for the sandy loam based on the values used by Arora et al. (2007) and Timsina et al. (2008). The soil evaporation stage 2 parameter (cona) was set to 2 mm based on the above studies.

All wheat crop simulations used the variety PBW343 established at 150 plants m^{-2} with a row spacing of 20 cm, and were irrigated when the soil water content (0-60 cm) had decreased to 50% of plant available water content (50% soil water deficit, SWD). The amount of water added to wheat crop at each irrigation was 120% of SWD to represent the inherent inefficiency of flood irrigation. All rice crop simulations used the long duration (155 days) variety PR118 (photoperiod insensitive) with 25 day old seedlings transplanted at 33 plants m^{-2}. Nutrients were non-limiting in all simulations. The results of all simulations were analysed in terms of grain yield, components of the water balance, and water productivity.

Wheat

Effect of sowing date

The calibrated APSIM model for wheat (Balwinder-Singh et al., 2011) was used to evaluate a range of sowing dates from 10 October to 30 December, at 10 day increments for potential yield (no water and nutrient stress) and under more realistic conditions with irrigation scheduled at 50% SWD.

Effect of mulch x sowing date

The interactions between mulching treatment (with and without mulch) and sowing date on growth, yield and water balance components were studied. Wheat sowing dates started from 15 October (middle of the rice harvesting season in Punjab) with an increment of 8 days up to 16 November. For all these simulations, 8 t ha^{-1} of rice straw was put as mulch on the soil surface on 15 October to simulate the situation after rice harvest. For non-mulched treatments, the rice straw was removed one day before sowing, simulating burning of rice straw one day prior to sowing. Both the mulched and non-mulched wheat were sown with zero tillage. Irrigations were scheduled at 50% SWD.

Rice

Effect of transplanting date

The APSIM-Oryza (Version 7.3) rice module was calibrated using ACIAR project data (LWR2/2000/089 and CSE/2004/033) for the long duration rice cultivar (PR118) (Humphreys et al., 2008; Yadvinder-Singh et al., 2009). The calibrated model was used to compare 8 transplanting dates from 1 May to 11 July at 10 day increments. The crop was irrigated daily as needed to maintain continuous ponding (depth 5 cm) for the first two weeks after transplanting. Irrigation water was applied daily to top up the paddy to 5 cm. Thereafter, the crop was irrigated 2 days after disappearance of the ponded water, and the amount of water added was the amount required to fill the top two soil layers (0-30 cm) to saturation plus an additional 50 mm water to create a temporary surface pond.

Rice-Wheat system

The effects of the rice irrigation schedule and post harvest rice residue management on individual rice and wheat crop and total system yield and water productivity were studied for rice transplanted at the optimum time (see section 3.3). Six rice irrigation schedules were compared: continuous flooding (maintaining 5 cm pond until maturity) (CF), and irrigation 2, 4, 7, 10 and 15 days after disappearance of the pond water (2-d, 4-d, 7-d, 10-d, 15-d). At each irrigation, the amount of water added was enough to saturate the topsoil and create a 50 mm temporary pond (as above). The rice was followed by wheat sown using zero tillage following rice straw removal (farmer practice), or zero till wheat with rice residues retained. In the straw removed scenario, the rice residues were removed one day after harvest and one pre-sowing irrigation of 70 mm was applied seven days before wheat sowing on 1 November. There was no pre-sowing irrigation for the rice residues retained treatment because of conservation of soil moisture by the mulch.

The results of the simulations were analysed in terms of grain yield, components of the water balance and water productivity. The components of the water balance examined were irrigation amount, soil evaporation, transpiration, ET, deep drainage beyond 180 cm and runoff. Water productivity was computed with respect to ET (WP_{ET}) and irrigation (WP_I).

Results

Optimum wheat sowing date

Potential grain yield was strongly affected by sowing date and by seasonal weather conditions (Figure 13.1a). For example, with sowing on 10 November, potential yield ranged from 3.0 t ha^{-1} to 8.5 t ha^{-1}. Potential yield was usually highest with 20 November sowing (mean 6.5 t ha^{-1}), closely followed by 10 November sowing (mean 6.3 t ha^{-1}). Potential yield increased as sowing date was delayed from 10 October (mean 4.0 t ha^{-1}) to 20 November, and then declined with delay in sowing beyond that. Average potential yield decreased by 68 kg ha^{-1} day^{-1} (1.1 % d^{-1}) with delay in sowing from 20 November to 30 December.

Table 13.1. Effect of sowing date on grain yield, irrigation amount, irrigation water productivity (WP_I) and crop water productivity (WP_{ET}) for water non-limiting (potential yield) and irrigation scheduled at 50% SWD

	10-Oct	20-Oct	30-Oct	10-Nov	20-Nov	30-Nov	10-Dec	20-Dec	30-Dec
Potential yield									
Grain yield ($t\ ha^{-1}$)	2.9	4.3	5.5	6.3	6.4	5.8	5.0	4.4	3.7
WP_{ET} ($kg\ ha^{-1}mm^{-1}$)	6.3	8.7	10.9	11.9	11.9	11.1	9.8	8.6	7.5
50%SWD									
Grain yield ($t\ ha^{-1}$)	2.7	3.9	5.2	5.6	5.0	4.2	3.5	2.9	2.5
Irrigation (mm)	127	186	232	247	242	229	212	186	169
WP_{ET} ($kg\ ha^{-1}mm^{-1}$)	10.8	12.5	14.3	14.4	13.2	11.6	10.2	9.0	8.1
WP_I ($kg\ ha^{-1}mm^{-1}$)	21.3	21.1	22.4	22.5	20.4	18.4	16.4	15.2	14.6

With irrigation at 50% SWD, yield was again strongly affected by both sowing date and seasonal conditions (Figure 13.1b). However, the yield trends as affected by sowing date varied in some ways from those for potential yield. In particular, the optimum sowing date was earlier (10 November), followed by 30 October. For each sowing date, potential yield was always higher than yield with 50% SWD scheduling. This was due to soil water deficit stress with irrigation scheduled at 50% SWD. For example, in 1997, potential yield of the 10 November sowing was 6.6 t ha^{-1}, compared with yield of 5.7 t ha^{-1} with irrigation at 50% SWD with an average water stress index of 0.94. More irrigation water was required by 10 November sowing than all other sowing dates. However, 10 November was optimum in terms of grain yield, WP_I and WP_{ET}.

Optimum sowing date for mulched wheat

There were interactions between wheat sowing date and mulching treatment on grain yield, ET and irrigation amount. In most years, yield with mulch was higher than yield without mulch, for all sowing dates. However, the positive effect of mulch on yield was larger, and occurred more often, for the 23 and 31 October sowing dates (Figure 13.2a) (Table 13.2). For example, the yield advantage with mulch for 23 October sowing ranged from 500 to 1200 kg ha^{-1} (average 900 kg ha^{-1}) whereas with 16 November sowing, mulch had a negative effect on yield in 40% years and the yield difference ranged from -600 to +700 kg ha^{-1} (average 90 kg ha^{-1}) (Table 13.2).

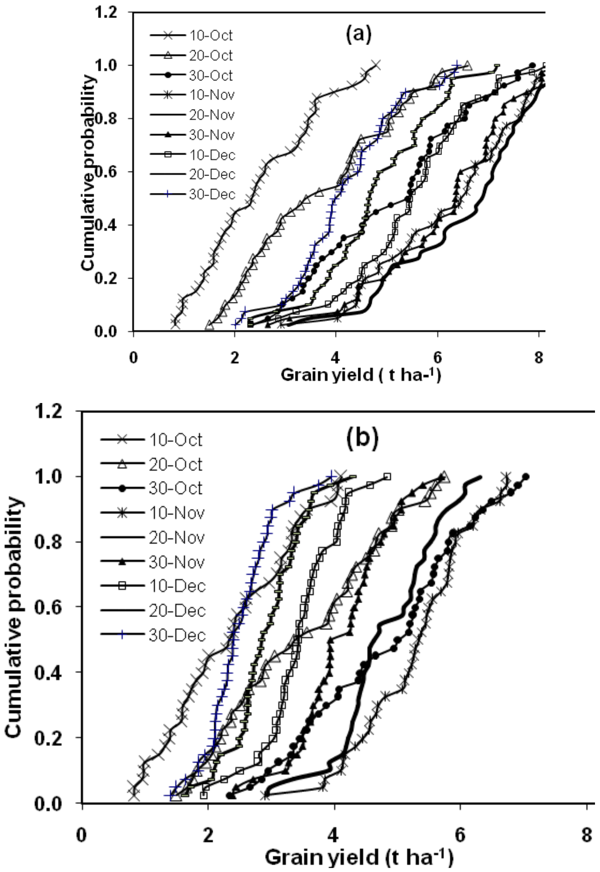


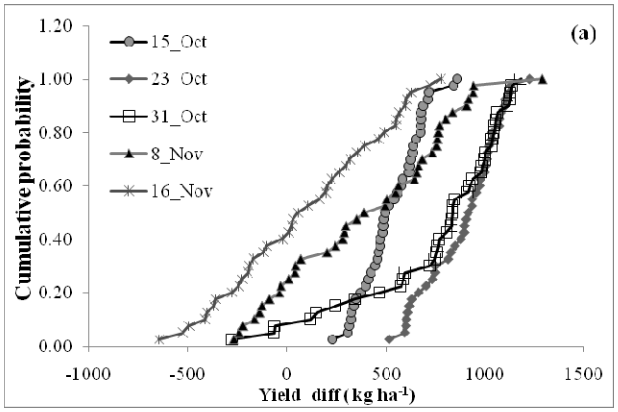
Figure 13.1. Effect of sowing date on (a) potential grain yield of wheat, (b) grain yield with irrigation scheduled at 50% SWD on a sandy loam

Table 13.2. Absolute yield levels (kg ha^{-1}) and difference between mean values for mulched and non-mulched wheat (mulch minus non-mulch) for grain yield (kg ha^{-1}), irrigation water input (mm) and crop ET (mm) for different sowing dates

	15 Oct	23 Oct	31Oct	8 Nov	16 Nov
Absolute yields (kg ha^{-1})					
Non-mulch	3200	4800	5100	5300	5000
Mulch	3830	5700	5850	5700	5090
Differences (mulch minus non-mulch)					
Yield (kg ha^{-1})	+530	+900	+750	+400	+90
Irrigation amount (mm)	+47	+5	0	-19	-23
ET (mm)	-1	+3	0	+10	+15

The effect of mulch on crop ET was small but variable within all sowing dates, and ranged from -22 to +33 mm (data not presented). For all three October sowing dates, mulch reduced ET in about 50% years. With 8 and 16 November sowing, mulch reduced ET in 70 and 95% of years, respectively. The effect of mulch on ET was driven by its effects on soil evaporation (Es) and transpiration. Mulch suppressed Es for all sowing dates in all years (except for 15 October sowing in 1 year). The effect of mulch on Es was variable within all sowing dates (range +6 to -53 mm). Averaged over all sowing dates for all 40 years, mulch reduced Es by 36 mm.

The effect of mulch on irrigation requirement was also variable, usually resulting in either 1 less irrigation, no effect, or 1 more irrigation (Figure 13.2b). Mulch reduced the irrigation requirement more with November sowings than October sowings. For 8 and 16 November sowings mulch reduced irrigation requirement by 1 irrigation (about 65 mm) in 32 and 40% of years, compared with a reduction in only 12% of years for October sowings (Figure 13.2b). In about 50% years under October sowings there was no effect of mulch on irrigation amount. The increase in irrigation requirement with mulch in some years was associated with higher biomass production and longer growth duration.



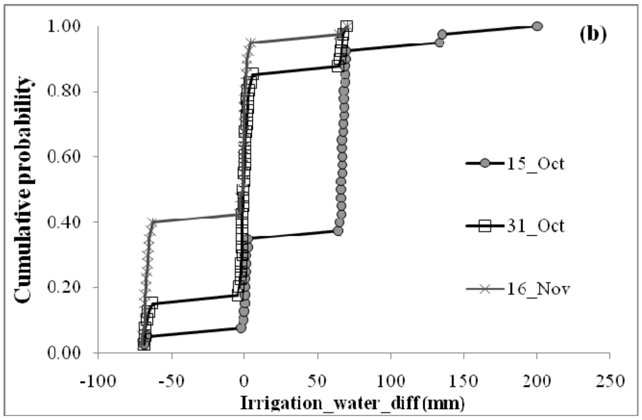


Figure 13.2. Effect of sowing date on difference between mulched and non-mulched wheat (mulch minus non-mulch) for (a) grain yield (b) irrigation water input

Mulch gave higher yield and maximum advantage in terms of grain yield under late October and early Novemeber sowings, but with less chance of reducing irrigation amount than for late November sowings. The yield and irrigation water productivity of mulched wheat were higher under early November than mid/late October sowings (data not presented). Based on these results, the optimum sowing date of mulched wheat is the first week of November, which will avoid grain filling during hot weather.

Optimum rice transplanting date

There was a consistent trend for a small but steady increase in grain yield as transplanting date was delayed from late May (6.1 t ha^{-1}) to early July (6.6 t ha^{-1}), with similar yield for all transplanting dates in May (Figure 13.3). The average amount of in-crop rainfall varied from around 475 mm for the earliest and latest transplanting dates, and increased to a maximum of around 560-570 mm for late May to late June plantings.

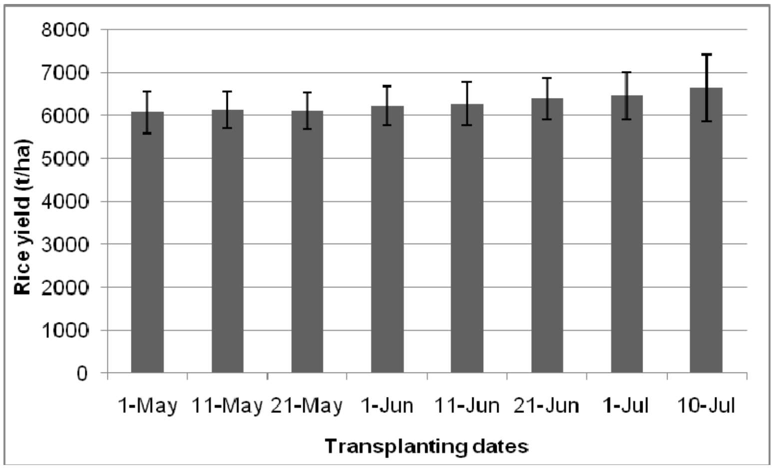


Figure 13.3. Effect of different rice transplanting dates in grain yield (kg/ha). Error bars represent standard deviation.

There was steady decline in ET with delay in transplanting from 1 May (835 mm) to 11 June (674 mm), beyond which ET only declined very slightly (Figure 13.4). As a result of trends in ET and rainfall, irrigation requirement declined from a maximum of 1,220 mm with 1 May transplanting to a minimum of 970 mm with 11 June transplanting, and then increased gradually as transplanting date was further delayed. Water productivity based on ET (WP_{ET}) increased steadily as planting was delayed from 1 May (7.3 (kg ha^{-1}mm^{-1}) to 10 July (10.3 (kg ha^{-1}mm^{-1}) due to both declining ET and increasing yield with delay in transplanting (Figure 13.5). However, irrigation water productivity (WP_I) was maximum for plantings around mid to end of June. In this case, there are tradeoffs between yield, irrigation amount, WP_{ET} and WP_I in determining optimum transplanting date. For a farmer for whom irrigation water is not limiting, delayed planting to 11 July would maximise yield, and this is also the best option in terms of minimising water depletion as ET and maximising WP_{ET}. However, if irrigation water is limiting, the best option for the farmer would be to transplant in late June.

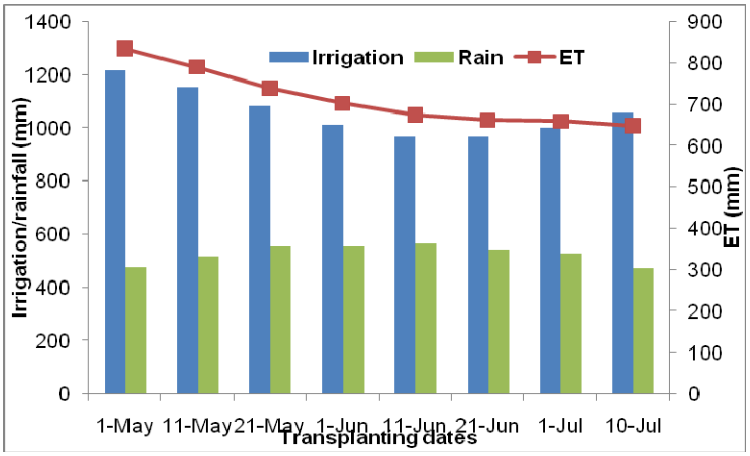


Figure 13.4. Rainfall, Irrigation and rice crop ET under different transplanting dates

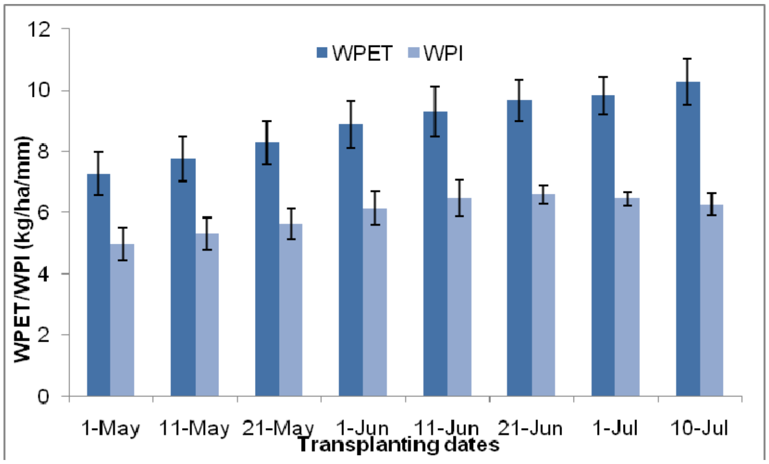


Figure 13.5. Water productivity based on ET and irrigation water applied under different rice transplanting dates. Error bars represent standard deviation.

Effect of rice irrigation schedule and residue management on rice-wheat system productivity

Rice

Grain yield was similar for CF, 2-d and 4-d irrigation schedules (mean 6.2 t ha^{-1}), and then declined steadily with decreasing frequency of irrigation to 4.4 t ha-^{1} with 15-d irrigation scheduling (Figures 13.6, 13.7). Rice grain yield was also more stable in the more frequent irrigation treatments (CF, 2-d and 4-d) and never fell below 5 t ha^{-1} (Fig 7). In contrast, yields of the 7, 10 and 15-d treatments fell as low as 3.6, 1.6 and 0.6 t ha^{-1}, respectively. Although there was no difference in yield of CF, 2-d and 4-d treatments, there was a big difference in irrigation amount (Figure 13.8). The highest irrigation amount was under CF (range 742 to 1860 mm) which was greatly reduced when irrigation was switched to AWD. The mean irrigation amount with CF (1163 mm) was reduced by 340 with 2-d. With further decrease in irrigation frequency, the irrigation amount was further decreased but by smaller amounts and with increasing yield penalty. For example average irrigation input reduction was 433 mm when changing from 4-d to 15-d irrigation schedule with an average yield penalty of 1.9 t ha^{-1}.

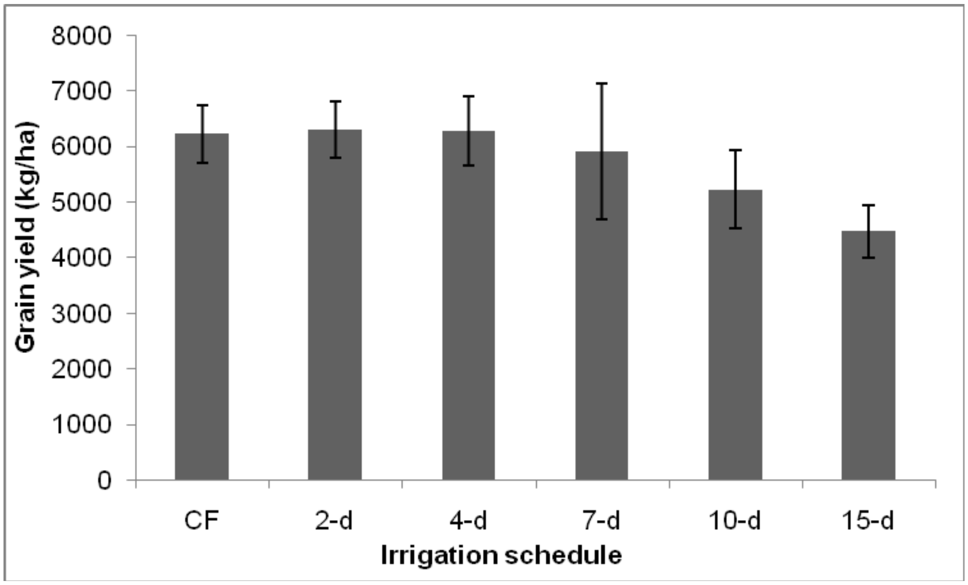


Figure 13.6. Average rice grain yields under different irrigation schedules. Error bars represent standard deviation of the data.

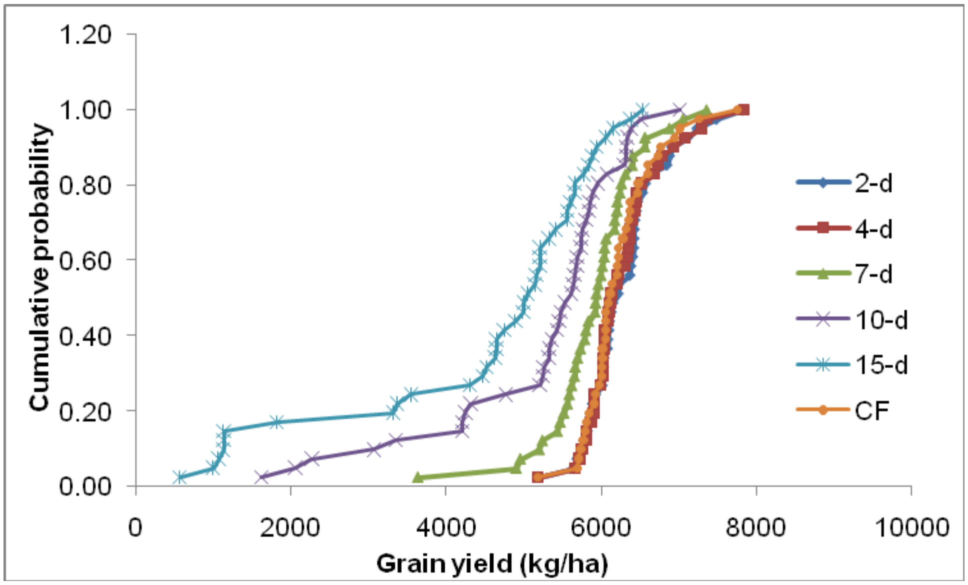


Figure 13.7. Cumulative probability of rice grain yield under rice irrigation schedules based on 40 years data

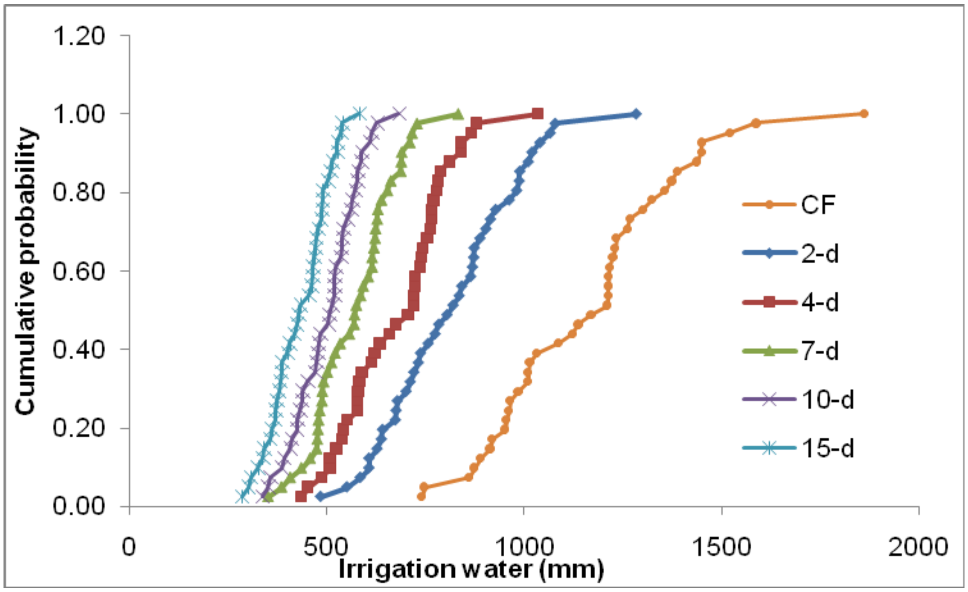


Figure 13.8. Cumulative probability of rice irrigation input under rice irrigation schedules based on 40 years data

Rice crop ET ranged from 477-890 mm for CF and similar ET for CF, 2-d and 4-d irrigation scheduling (670 to 675 mm). There was a small decline in ET as irrigation frequency was reduced beyond 4-d, with a 12% reduction to an average value of 601 mm for 15-d. Average WP_I was increased from 5.5 to 8.0 (kg $ha^{-1}mm^{-1}$) as irrigation management changed from CF to 2-d, and increased further with less frequent irrigation. WP_I was less variable under CF, 2-d, 4-d than less frequent irrigation treatments (Figure 13.9).

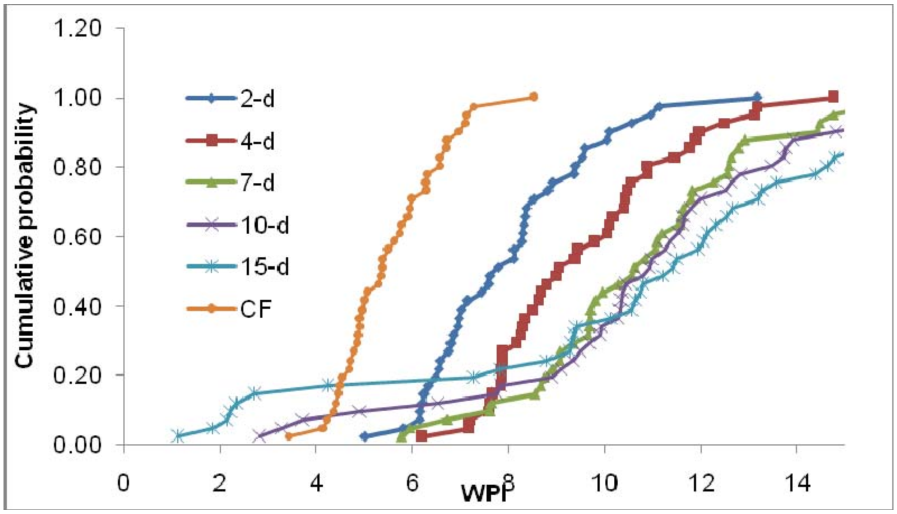


Figure 13.9. Cumulative probability of rice irrigation water productivity under rice irrigation schedules based on 40 years data

WP_{ET} was similar for CF, 2-d and 4-d irrigation schedules (consistent with their similar yield and ET) and ranged from 5.7 to 11.4 (kg $ha^{-1}mm^{-1}$). WP_{ET} was more variable under 7-d, 10-d and 15-d irrigation treatments. The average WP_{ET} achieved was the same all irrigation treatments which is 9.3 (kg $ha^{-1}mm^{-1}$) except 10-d and 15-d irrigation where it was low at 8.2 and 7.4 (kg $ha^{-1}mm^{-1}$) respectively.

Wheat

Wheat yield (mean 5.8 t ha-^{1}) was not affected by mulching treatment nor by irrigation scheduling for rice (Figure 13.10). However, there was in interaction between rice irrigation schedule and rice residue management on wheat irrigation input due to differences in soil profile water content at the time of rice harvest. The mean residual soil water content (0-180 cm) at rice harvest was 478, 432, 405, 381, 364, 354 mm under CF, 2-d, 4-d, 7-d, 10-d and 15-d rice irrigations schedules, respectively. With CF, 2-d, 4-d rice irrigation schedules, the irrigation requirement for mulched wheat was lower than for non-mulched wheat. However, with less frequent irrigation scheduling for rice, the wheat irrigation requirement was similar with and without mulch. The mean difference in irrigation amount to non-mulched wheat compared with mulched wheat decreased from +43 to -8 mm with decrease in rice irrigation frequency from CF to 15-d. There was an increase in irrigation input to wheat as the frequency of irrigation of rice was delayed from CF to 15-d, much more so for non-mulched wheat. For non-mulched wheat, the irrigation amount increased from 277 to 312 mm as rice irrigation frequency decreased from CF to 15-d.

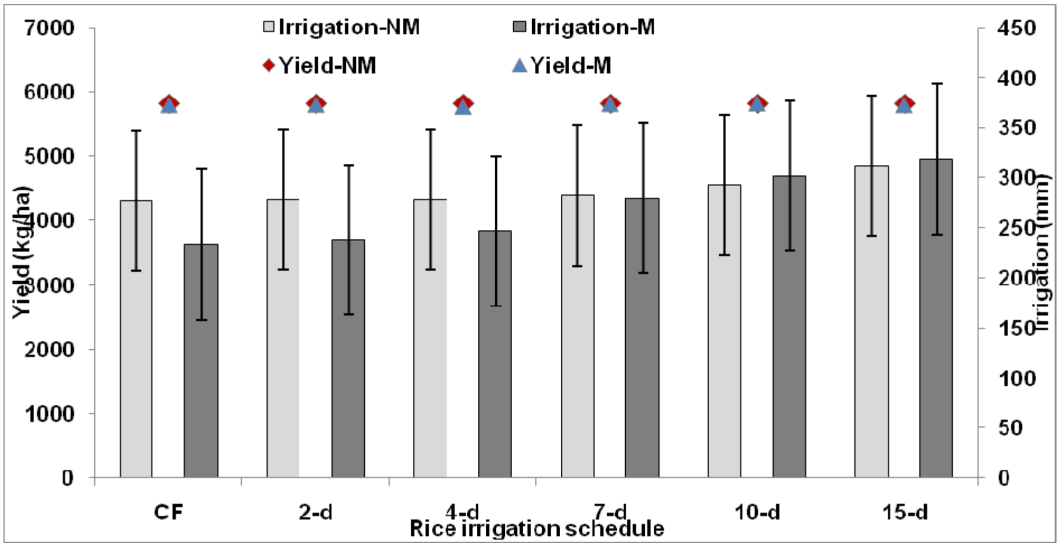


Figure 13.10. Wheat grain yield and irrigation water input under mulch and non-mulched treatments following different rice irrigation schedules. M-mulch and NM-non-mulch. Error bars represent standard deviation of the data.

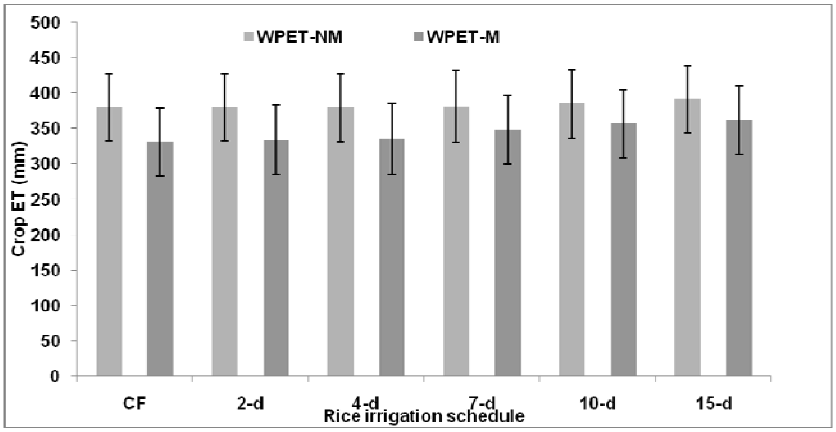


Figure 13.11. Wheat crop ET under mulch and non-mulched treatments following different rice irrigation schedules. M-mulch and NM-non-mulch. Error bars represent standard deviation of the data.

The mulched wheat had lower ET than non mulched wheat, but the difference gradually decreased as irrigation frequency decreased from CF (49 mm) to 15-d (30 mm) (Figure 13.11). Trends in ET were similar to trends in yield for mulched and non-mulched wheat, respectively.

WP_{ET} of mulched wheat decreased slightly with delay in irrigation of rice from CF to 15-d, but there was only a very small effect of rice irrigation treatment on WP_{ET} of non-mulched wheat (Figure 13.12a). At each rice irrigation level, mulched wheat had higher WP_{ET} than non- mulched wheat, but the absolute differences decreased with delay in irrigation. Similar trends were observed for WP_I but the rate of decrease of WP_I in mulched wheat with delay in rice irrigation was much higher than for WP_{ET} (Figure 13.12b).

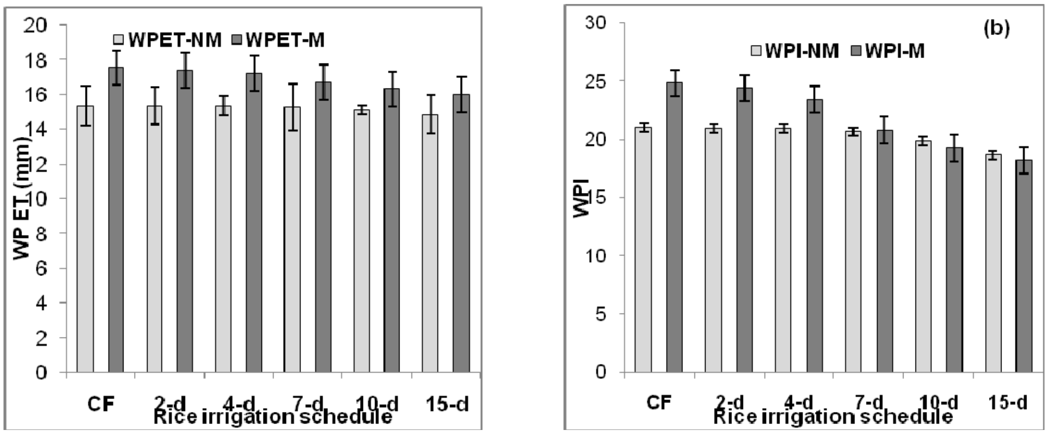


Figure 13.12. Wheat water productivity based on ET (a) and irrigation water applied (b) as affected by rice residue management and rice irrigation schedule. Error bars represent standard deviation of the data.

Total rice-wheat system

Total rice-wheat (RW) system yield (rice yield + wheat yield) was not affected by rice residue retention, but followed the yield trends for rice as affected by irrigation schedule (Figure 13.13a). Total system irrigation input was always higher in the non-mulched than mulched system, but the difference declined as rice irrigation frequency decreased from CF to 15-d.

ET of the rice-wheat system (not including fallows) decreased slightly with delay in rice irrigation, and the mulched system had lower ET than the non-mulched system within each rice irrigation level (data not presented). Total system ET was highest with CF (mean 1055 mm) and decreased to 993 mm with 15-d irrigation scheduling and non-mulched wheat. Total system WP_{ET} was similar for CF, 2-d and 4-d rice irrigation schedules irrespective of rice residue management, but decreased with further delay in rice irrigation, more so in the mulched system.

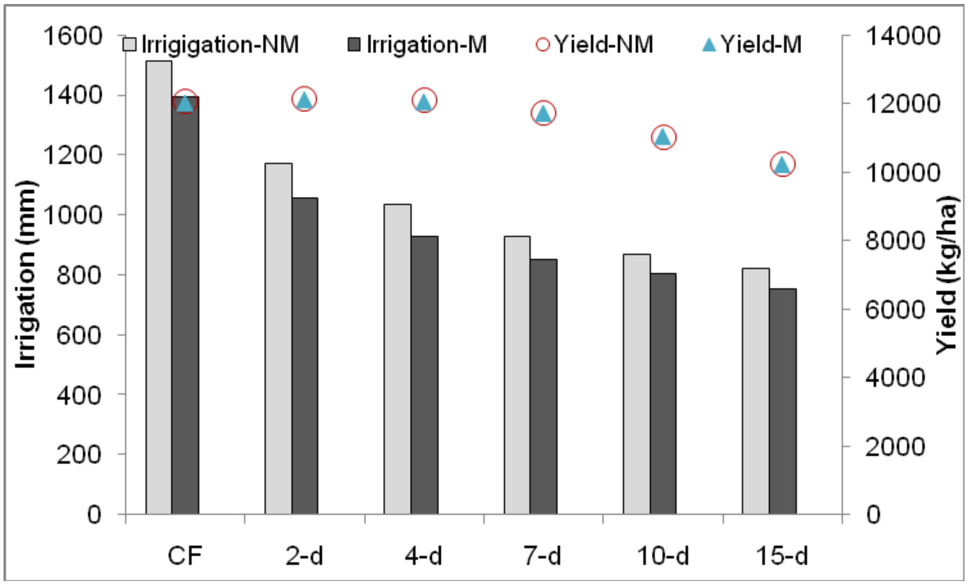


Figure 13.13. Rice wheat system irrigation water input and grain yield (rice+wheat) under rice residue management and different irrigation schedules.

There was a large effect of rice irrigation scheduling on total rice-wheat system WP_I and a relatively small effect of rice residue management in the more frequently irrigated treatments only. The lowest WP_I 8.0 (kg $ha^{-1}mm^{-1}$) occurred in the system with CF rice, which increased markedly to 11.0 (kg $ha^{-1}mm^{-1}$**)** when rice irrigation switched to 2-d, with a small increase to a maximum of around 13.7 (kg $ha^{-1}mm^{-1}$) for 7 to 15-d irrigation schedules (Figure 13.14).

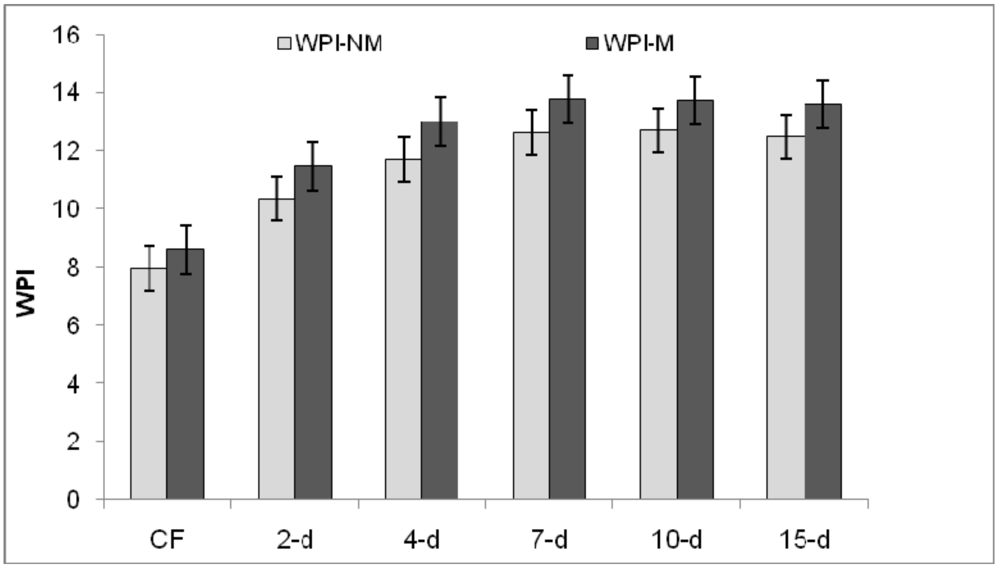


Figure 13.14. Irrigation water productivity of the rice wheat system as affected by rice irrigation scheduling and rice residue management. Error bars represent standard deviation of the data.

Discussion

Wheat sowing date

The large variability in potential grain yield between years was due to seasonal variability. For example, for 10 November sowing, the highest potential yield (8.5 t ha^{-1} in 1988-1989) was associated with high solar radiation from tillering to anthesis, consistent with the findings of Fischer et al. (2007) that solar radiation during the 15-20 d period before anthesis is important for biomass production and potential grain number. The lowest potential yield (3.0 t ha^{-1} in 1976-1977) was associated with low solar radiation and hence low biomass production during the vegetative phase (sowing to anthesis) and low total biomass at anthesis. In 1976-1977 the grain number was very low (5,700 grains m^{-2}) compared to the average of 12,780.

With 50% SWD irrigation scheduling, maximum grain yield was observed with sowing on 10 November, while WP_{ET} and WP_I were highest for sowing around 30 October-10 November. Thus in terms of maximising yield, WP_{ET} and WP_I, the optimum sowing date was early November. The lower grain yield of early sowings was associated with lower grain number due to a shorter vegetative growth period and lower LAI and biomass production. The lower grain yield with later sowing was associated with both lower grain number (due to higher water stress) and lower grain weight, as the grain filling period falls in increasingly hotter weather as sowing is delayed. These results are similar to those of the modelling study of Arora and Gajri (1998).

In field studies over seven years at Ludhiana, the optimum sowing date for maximum yield was 15 November for varieties (PBW 154 and PBW 226) with similar duration to that of PBW 343 (Ortiz-Monasterio et al., 1994). They found that grain yield decreased by about 0.7% per day delay in sowing beyond this date. In another field study, Randhawa et al. (1981) reported that with delay in sowing from 25 October to 15 December, grain yield of Kalayansona, WL711, HD2009 and WG 357 varieties decreased by 1.2, 0.9, 1.2 and 1.0% per day delay in sowing after 25 October, respectively. In our simulations grain yield decreased by 0.7-1.0% per day delay in sowing beyond 10 November, consistent with the findings of the above field studies.

While the results of our simulations of the effect of sowing date on potential yield using APSIM were consistent with those using other crop models in this environment (Arora et al., 2007; Arora and Gajri, 1998; Timsina et al., 2008), the magnitude of potential yield within each sowing date varied between the studies. The simulated average yields of Arora and Gajri (1998) with the SUCROS-WBM model (3.6 and 6.0 t ha^{-1} for 15 October and 15 November sowings, respectively) were similar to our results using APSIM. Using DSSAT-CSM-CERES Wheat version 4.0, Timsina et al. (2008) also predicted similar maximum average potential grain yield of PBW 343 (6.3-6.4 t ha^{-1}) for sowings from 25 October-25 November, however mean yield for the 10 October sowing (5.2 t ha^{-1}) was much higher than the 3 t ha^{-1} predicted by Arora and Gajri (1998) and our study using APSIM. The variable results point to the desirability of some common data sets and comparative model studies. Accurate assessment of potential yield is important in; determining the gap between crop potential and on-farm yields; helping prioritise research investment in reducing this gap and increasing farm productivity.

Wheat sowing dates and mulch

The optimum sowing date of mulched wheat for maximum yield and maximum yield advantage as compared to non-mulch was 23 October, and there was a decrease in the yield advantage with mulch in earlier and later sowings. In contrast, Sidhu et al. (2007) did not find a significant interaction between sowing date and residue management in field experiments in the same location. Simulations indicate that on average, the yield advantage with mulch decreased from 890 kg ha^{-1} to 95 kg ha^{-1} with delay in sowing from 23 October to 16 November (4% d^{-1}). The yield decline after the optimum sowing date is explained by decline in grain number and grain weight. The mulched wheat sown in late October had higher grain number and grain weight than the non mulched wheat while under later sowings mulched and non mulched wheat had similar grain number, but mulched wheat had lower grain weight. In the model, potential grain number is based on biomass at anthesis, and the biomass at anthesis was higher in the mulched crop sown in late October. The higher biomass was the result of a longer vegetative phase in the mulched crop. However, the longer vegetative phase did not result in grain filling of the late October sown crops during periods of higher temperatures. This extension in the vegetative period due to mulch was decreased slightly with later sowings due to the exposure of the crop to relative high temperature. For example, flowering date of the 23 October sowing was delayed by 6 days under mulch compared with a 4 day delay for 16 November sowing and this was reflected by less advantage under mulch (more than 1 t ha^{-1}) in biomass accumulation at anthesis. However, where there was yield loss with mulch under late sowings, this was more related to lower grain weight due to exposure of the crop to higher temperature during grain filling. Within each sowing date, the mulched wheat on average experienced 1.1°C higher temperature during grain filling than the non-mulched wheat, but as temperatures were much higher during grain filling for later sown crops, the effect of an additional 1.1°C on the mulched crops had a more detrimental effect. For 23 October sowings, average temperature during the grain filling period was 23°C (without mulch), compared to 29°C for the 16 November sown crop. However, under irrigated conditions, a temperature of 29°C would not be as detrimental to grain filling as shorter exposure to extremely high temperature (>34°C). In 40 years, the number of days on which the crop was exposed to temperature >34°C increased as sowing was delayed. For the 15 November sowing there was a significant number of years and days in which the crop was exposed to even higher temperature (>40°C) during grain filling. High temperature during grain fill slows the rate of grain filling because of damage to the photosynthesis apparatus and which also results in acceleration of senescence and shortening of the grain filling period (Al-Khatib and Paulsen, 1984; Zhao et al., 2007).

The higher water saving under mulch in late sowings (November sowings) result in a yield penalty (explained above), the crop requires less water and produces less yield. So there is trade-off between yield and water savings as we move from October to November sowings. In 15 October sowing mulch crop required higher irrigation water in some years to support higher biomass production as compare to non-mulch crop and in some years one extra irrigation due to longer crop duration under mulch. Higher number of irrigations under mulch resulted in more wetting events and hence high soil evaporation losses as compare to non-mulched crop.

Rice transplanting date

In contrast with our model results, most field studies in north-west India conclude that yields are stable or decrease when transplanting is delayed from May to July. However, the results may vary from year to year depending on weather and build up of insect and disease pressure as the season progresses. Using the CROPMAN model, Chahal et al. (2007) showed an increasing trend in yields from 1 May transplanting to 1 July transplanting using PR118, the same variety used in our study. In their study they also considered PR118 to be a photo-insensitive cultivar and showed that the lower radiation and temperature during early crop growth in late transplanted crops did not lower yield as argued by other researchers (Mahajan et al., 2009). Chahal et al., (2007) hypothesised that the later transplanted crop was less exposed to “super thermal temperature” (>37°C) and that this may be the reason for increasing trend in the yield in July transplanted crops.

Early transplanted crops were exposed to higher evaporative demand after transplanting and thus required more frequent irrigation, resulting in higher Es and T (Figure 13.15). In Punjab 40-45% of annual open pan evaporation occurs during the 2 months from mid-April to mid-June (Minhas et al., 2010). Thus, total pan evaporation during our 1 May transplanted crop was 846 mm compared to 628 mm during the 1 July transplanted crop. Crops exposed to high vapour pressure deficit during crop growth have lower photo assimilation per unit of water consumed and increased respiration due to higher day temperature (Kropff et al., 1993). The decrease in ET with delay in transplanting was due to both decrease in T and Es, but more due to decrease in T. Chahal et al. (2007), Arora (2006) and Singh et al. (1996) also reported a decrease in ET with delay in transplanting from early May to July.

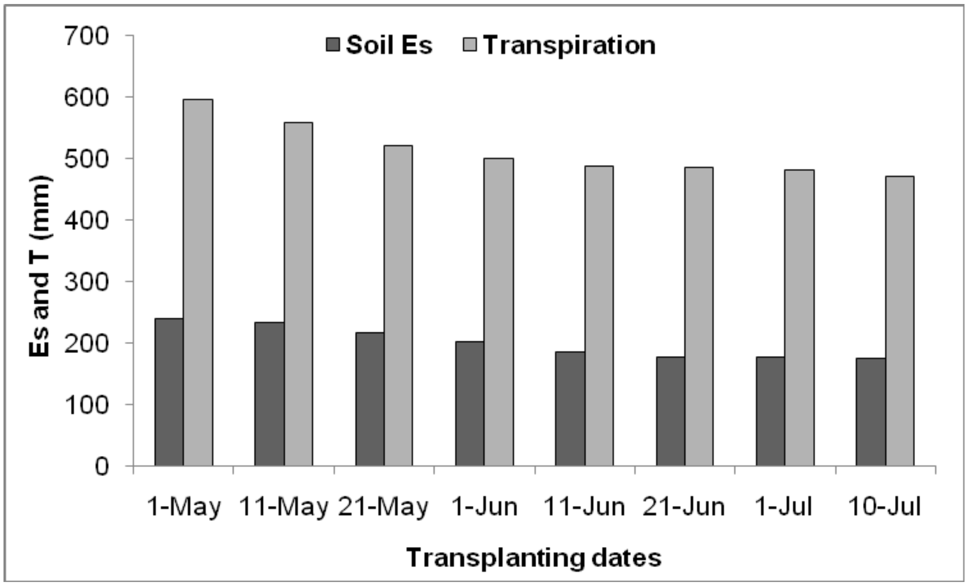


Figure 13.15. Soil evaporation and crop transpiration from rice for different transplanting dates

Rice irrigation schedule

The main reasons for much higher water use in flooded rice than other crops are high seepage and percolation losses. Reduction of hydrostatic pressure is an important means for reducing such losses (Bouman et al., 1994). This is the principle behind AWD, also known as intermittent irrigation. This involves flooding the field to a shallow depth (e.g. 50 mm), allowing the water to dissipate, and re-irrigating some time after the soil surface has dried out. It has been well-established that irrigation input can be reduced by the use of safe AWD (i.e. AWD managed to avoid yield loss). The reduction varies from 10-40% of the amount applied to a continuously flooded field, depending on soil hydraulic conductivity and depth to the water table. In our study on a sandy loam soil, shifting to safe AWD from CF saved 25% of irrigation water which is consistent with the results from other field studies (Chaudhary et al., 2006; Hira et al., 2002; Sharma et al., 1989, 1999; Sudhir-Yadav et al., 2011a) and modelling studies (Arora, 2006; Sudhir-Yadav et al., 2011b). Irrigation water reduction was mainly due to reduction in deep drainage beyond root the zone. On average, deep drainage was reduced by the same amount as irrigation water when switching from CF to 2-d, however the reduction in deep drainage was quite variable from year to year depending on rainfall. With introduction of AWD there was no change in the crop ET with decreased frequency up to and including the 4-d irrigation schedule because the topsoil remains wet (above field capacity) between irrigations and irrigation water was applied before Es entered a reduced rate stage (stage 2 evaporation), so there was no difference in Es under these irrigation schedules. However, with further delay in irrigation to the 7-d, 10-d and 15-d schedules, the soil dried more and the rate of Es decreased. In these treatments water stress also caused a reduction in transpiration and total biomass.

In wheat, the frequent rice irrigation treatments resulted in an almost full soil profile at the time of rice harvest, which reduced the need for irrigation of wheat. Wheat is able to use the moisture stored deep in profile after rice. Gajri et al. (1993) reported that one early season irrigation at about 30 d after sowing can force the crop to use the profile water resulting in yields as high as that achieved with more frequent irrigation. Keeping the rice residue as surface mulch reduced the wheat irrigation water requirement more in the frequent rice irrigation treatments because the need for irrigation of these treatments was delayed until the crop had dried the soil profile to 50% SWD, whereas crops starting with a drier soil profile needed irrigation sooner. It is well established that mulch is only effective in reducing Es when soil is wet and Es is at potential rate (stage 1 evaporation) (Bond and Willis, 1970). Therefore the difference between non-mulch and mulch system wheat Es decreased with delay in rice irrigation (Figure 13.16). Laboratory studies showed that in a single drying cycle, cumulative evaporation from straw-mulched soil initially lagged behind that from non-mulched soil, but with time, total water loss from the mulched soil was similar to or exceeded that of non-mulched soil (Jalota and Prihar, 1990; Jalota, 1993).

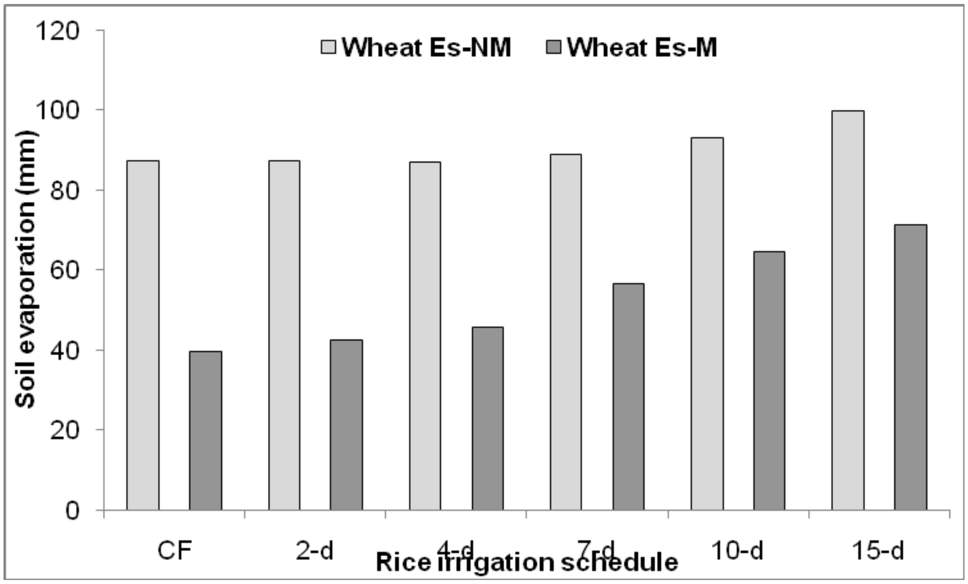


Figure 13.16. Soil evaporation under mulched and non-mulched wheat as function of rice irrigation schedules

Rice-wheat system

In the total rice-wheat system, rice received about 80% of the total irrigation water input under CF and non-mulched wheat, and rice also accounted for more than 60% of total system ET (not including Es during the fallow). Any crop management practice which affected irrigation water input and rice ET had a significant effect on system irrigation and ET and system irrigation water productivity. For example when switching from CF to 2-d rice irrigation there was significant increase in system irrigation water productivity. Although wheat received much less irrigation water than rice, there was scope to use the residual soil profile water after rice harvest. A combination of water saving practices like optimum rice transplanting date with safe AWD followed by timely sowing of wheat with surface mulch can have significant effect on system water compared to current farmer practices.

Conclusions

Crop management practices, especially sowing/transplanting dates and irrigation water management, are potential irrigation water saving practices in rice-wheat system in NW India. The optimum sowing date for mulched wheat for maximum yield and WP_I is late October to early November. Rice yields increased as transplanting was delayed from May to July, while irrigation water requirement declined from a maximum under May transplanting to a minimum with mid/late June transplanting. The higher irrigation input to May and July transplanting was due to higher evaporative demand and lower monsoon rainfall during the cropping season. WP_I was also higher with mid/late June transplanting but WP_{ET} was higher under July transplanting.

There was about 25% irrigation water saving when changing from CF rice to irrigation 2-d after the pond water had dissipated (2-d) without any yield decline, and further irrigation water savings (~50%) with no yield reduction with a 4-d irrigation schedule. Consistent with yields, there was no significant difference in crop ET under different rice irrigation schedules from CF to 4-d. Average WP_I was increased from 8.0 to 9.5 to 10.7 (kg $ha^{-1}mm^{-1}$) with changing rice irrigation from CF to 2-d to 4-d, respectively.

Wheat irrigation water input was reduced with surface retention of rice residues provided that the rice was irrigated sufficiently to maintain yield (CF, 2-d, 4-d), leaving a fairly full profile at the time of rice harvest. Total rice-wheat system yield was maximised with rice irrigated using 4-d scheduling and mulched wheat, and with higher WP_I than for CF and 2-d rice irrigation scheduling. Total system WP_I was higher under 7-d, 10-d and 15-d rice irrigation schedules, but there was high yield penalty when using these irrigation schedules.

References

Al-Khatib, K., and Paulsen, G.M. (1984) Mode of high temperature injury to wheat during grain development. Physiol. Plant 61, 363-368.

Ambast, S.K., Tyagi, N.K., Raul, S.K., (2006) Management of declining groundwater in the trans Indo-Gangetic plain (India): some options. Agric. Water Manage. 82, 279–296.

Arora, V. K. (2006). Application of a rice growth and water balance model in an irrigated semi-arid subtropical environment. Agric. Water Manage. 83, 51–57.

Arora, V.K, Gajri, P.R., (1998) Evaluation of crop growth-water balance model for analysing wheat responses to climate and water-limited environments. Field Crops Res. 59, 213-224.

Arora, V.K., Singh, H., Singh, B., (2007) Analyzing wheat productivity responses to climatic, irrigation and fertilizer-nitrogen regimes in a semi-arid sub-tropical environment using the CERES-Wheat model. Agric. Water Manage. 94, 22-30.

Balwinder-Singh, Gaydon D.S., Humphreys E, Eberbach P.L. (2011). Evaluating the performance of APSIM for irrigated wheat in Punjab, India. Field Crops Res., 124, 1-13.

Bond, J.J., Willis, W.O., (1970) Soil Water Evaporation: Ist stage drying as influenced by surface residue and evaporation potential. Soil Sci. Soc. Am. Proc. 34, 924-928.

Bouman, B.A.M., Wopereis, M.C.S., Kropff, M.J., Tenberge, H.F.M., Tuong, T.P., (1994) Water-use efficiency of flooded rice fields. 2. Percolation and seepage losses. Agric. Water Manage. 26, 291–304.

Chahal, G. B. S., Sood, A., Jalota, S. K., Choudhury, B. U., and Sharma, P. K. (2007). 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. Agric. Water Manage. 88, 14–22.

Choudhury, B. U., Bouman, B. A. M., and Singh, A. K. (2006). Yield and water productivity of rice–wheat on raised beds at New Delhi, India. Field Crops Res. 100, 229–239.

FAO, (2007) FAOSTAT Agricultural Production Database, Food and Agriculture Organization of the United Nations, Rome.

Fischer, R.A., (2007) Understanding the physiological basis of yield potential in wheat. J. Agric. Sci. 145, 99-113.

Hira, G. S., Singh, R., and Kukal, S. S. (2002). Soil matric suction: A criterion for scheduling irrigation to rice (Oryza sativa). Indian J. Agric. Sci. 72, 236–237.

Hira, G.S., (2009) Water management in northern states and the food security of India. J. Crop Improv. 23, 136–157.

Humphreys, E., Kukal, S.S., Amanpreet-Kaur, Thaman, S., Yadav, S., Yadvinder-Singh, Balwinder-Singh, Timsina, J., Dhillon, S.S., Prashar, A. and Smith, D.J. (2008). Permanent beds for rice-wheat in Punjab, India. Part 2: water balance and soil water dynamics. In 'Permanent beds and rice-residue management for rice-wheat systems in the Indo-Gangetic Plain'. Eds E. Humphreys and C.H. Roth. Proceedings of workshop held in Ludhiana, India, 7-9 September 2006. ACIAR Proceedings No. 127. Australian Centre for International Agricultural Research (Canberra, Australia). Pp. 37-61. Available at http://www.aciar.gov.au/publication/term/18

Humphreys, E., Kukal, S.S., Christen, E.W., Hira, G.S., Balwinder-Singh, Sudhir-Yadav, (2010) Halting the groundwater decline in North-West India – which crop technologies will be winners? Adv. Agron. 109, 155–217.

Jalota, S.K., (1993) Evaporation through a soil mulch in relation to mulch characteristics and evaporativity. Aust. J. Soil Res. 31, 131-136.

Jalota, S.K., Prihar, S.S., (1990) Effect of straw mulch on evaporation reduction in relation to rates of mulching and evaporativity. J. Indian Soc. Soil Sci. 38, 728-730.

Kropff, M.J., Centeno, G., Bachelet, D., Lee, M.H., Mohan Dass, S., Horie, T., Defeng, S., Singh, S., Penning de Vries, F.W.T., (1993) Predicting the impact of CO2 and temperature on rice production. In: IRRI Seminar Series on Climate Change and Rice, International Rice Research Institute, Los Banos, Phillipines.

Mahajan, G., Bharaj, T.S., Timsina, J., (2009) Yield and water productivity of rice as affected by time of transplanting in Punjab, India. Agric.l Water Manage. 96, 525–532.

Minhas, P.S., Jalota, S.K., Arora, V.K., Jain, A.K., Vashist, K.K., Choudhary, O.P., et al., (2010) Managing water resources for ensuing sustainable agriculture: situational analysis and options for Punjab. Research Bulletin 2/2010, Directorate of Research, Punjab Agricultural University, Ludhiana-141004 (India), 40.

Ortiz-monasterio, J.I., Dhillon, S.S., Fischer, R.A., (1994) Date of sowing effects on grain-yield and yield components of irrigated spring wheat cultivars and relationships with radiation and temperature in Ludhiana, India. Field Crops Res. 37, 169-184.

Randhawa, A.S., Dhillon, S.S., Singh, W., (1981) Productivity of wheat varieties, as influenced by the time of sowing. J. Res. (PAU) 18, 227-233.

Rodell, M., Velicogna, I., Famiglietti, J.S., (2009) Satellite-based estimates of groundwater depletion in India. Nature 460, 999–1002.

Sharma, B. R. (1999). Water saving irrigation techniques for paddy rice in India. International Symposium on Water Saving Irrigation for Paddy Rice Chinese National Committee on Irrigation and Drainage, Beijing, People's Republic of China, pp. 72–83.

Sharma, P. K. (1989). Effect of periodic moisture stress on water-use efficiency in wetland rice. Oryza 26, 252–257.

Sidhu, H.S., Manpreet, S., Humphreys, E., Yadvinder, S., Balwinder, S., Dhillon, S.S., Blackwell, J., Bector, V., Malkeet, S., Sarbjeet, S., (2007) The Happy Seeder enables direct drilling of wheat into rice stubble. Aust. J. Exp. Agric. 47, 844-854.

Singh, C.B., Aujla, T.S., Sandhu, B.S., Khera, K.L., (1996) Effect of transplanting date and irrigation regime on growth, yield and water use in rice (Oryza sativa L.) in northern India. Indian J. Agric. Sci. 66, 137–141.

Sudhir Yadav, Balwinder-Singh, Elizabeth Humphreys and Surinder Singh Kukal. (2012) Effective Management of Scarce Water Resources in North West India. In: Agricultural Sustainability: Progress and Prospects in Crop Research Editors: G. Bhullar and N.Bhullar. Elsevier publication,pp 103-121.

Sudhir-Yadav, Humphreys, E., Kukal, S.S., Gill, G., Rangarajan, R., (2011a). Effect of water management on dry seeded and puddled transplanted rice Part 2: water balance and water productivity. Field Crops Res. 120, 123–132.

Sudhir-Yadav, L Tao, E Humphreys, G Gill, and SS Kukal. (2011b). Evaluation and application of ORYZA2000 for irrigation scheduling of puddled transplanted rice in northwest India. Field Crops Res. 122: 104-177.

Tanwar, B.S., Kruseman, G.P., (1985) Saline groundwater management in Haryana State, India Hydrogeology in the Service of Man. Memoirs of the 18th Congress of the

International Association of Hydrogeologists, Cambridge, (pp. 24–30. Retrieved August 12, 2012 from <http://iahs.info/redbooks/a154/iahs_154_03_0024.pdf>).

Timsina, J., Godwin, D., Humphreys, E., Yadvinder, S., Bijay, S., Kukal, S.S., Smith, D., (2008) Evaluation of options for increasing yield and water productivity of wheat in Punjab, India using the DSSAT-CSM-CERES-Wheat model. Agric. Water Manage. 95, 1099-1110.

UNESCO (1995). United Nations Educational, Scientific, and Cultural Organization (UNESCO) Statistical Yearbook 1995. UNESCO, Paris, France.

Yadvinder-Singh, Bijay-Singh, Nayyar, V.K., Jagmohan-Singh, (2003) Nutrient Management for Sustainable Rice-Wheat Cropping System. National Agricultural Technology Project, Indian Council of Agricultural Research, New Delhi, India, and Punjab Agricultural University, Ludhiana, Punjab, India.

Yadvinder-Singh, Humphreys, E., Kukal, S.S., Singh, B., Kaur, A., Thaman, S., Prashar, A., Yadav, S., Timsina, J., Dhillon, S.S., Kaur, N., Smith, D.J., Gajri, P.R., (2009) Crop performance in permanent raised bed rice-wheat cropping system in Punjab, India. Field Crops Res. 110, 1-20.

Zhao, H., Dai, T., Jing, Q., Jiang, D. Cao, W., (2007) Leaf senescence and grain filling affected by post-anthesis high temperatures in two difference wheat cultivars. Plant Growth Regul. 51, 149-158.