Options for increasing the productivity of the rice-wheat system of north west India while reducing groundwater depletion. Part 2. Is conservation agriculture the answer?

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ABSTRACT

The irrigated rice-wheat system of north west India is not sustainable, as currently practised, due to over-exploitation of groundwater, soil degradation, labour scarcity, high fuel and labour costs, and air pollution from stubble burning. Labour and water scarcity are driving farmers to change from puddling and manual transplanting of rice to mechanised dry seeding. The introduction of dry seeding to the rice-wheat system brings with it the potential to adopt conservation agriculture (CA), with reduced or zero tillage for all crops, and surface residue retention. This would further reduce fuel and labour costs for crop establishment, and air pollution, and also bring benefits for soil structure and nutrient cycling. However, whether conversion to CA rice-wheat systems would help solve the problem of groundwater depletion is less well-understood. In this region, evapotranspiration (ET) must be reduced to reduce groundwater depletion. We used the APSIM cropping system model to examine whether conversion from recommended farmer practice (rFP, comprising puddled transplanted rice, alternate wetting and drying rice water management, rice straw removal, tillage for wheat) to a CA rice-wheat system would reduce ET in Punjab, north west India. We also used the model to identify the optimum system management taking into account effects on total cropping system rice equivalent yield (REY), components of the water balance and water productivity. Maximum REY (mean 14.6 t ha⁻¹) occurred in systems with 5 June sowing of a popular long duration rice variety, with similar yield for rFP and CA. Irrigation

input with CA was much lower (by 390 mm) than with rFP, resulting in slightly higher irrigation water productivity (increased from 11.3 to 11.7 kg ha⁻¹mm⁻¹). However, changing to CA only reduced ET of the highest yielding system by 4% (55 mm), and of other current practices (late May and early June sowing of medium and long duration varieties) by less than this. The only way to achieve a substantial reduction in ET was by growing short duration rice varieties in both the rFP and CA systems. However, with current short duration varieties, this came at the cost of both rice and system yields (system yield reduced by an average of about 1.8 t ha⁻¹). This could be overcome by intensification to 3 crops per year in a CA rice-wheat-mung system (with short duration rice varieties), while still providing a substantial but smaller decrease in ET. This system also had considerable flexibility in rice sowing date, with similar system yields for sowings from 5 June to 15 July. These findings suggest that greater effort to increase the yield potential of short duration rice varieties is warranted. Field experimentation is needed to test the improved systems as suggested by the model simulations, particularly in terms of cropping system yield and ET, and alternatives to rice and wheat should also be evaluated. At the same time, spatial hydrological studies are needed to determine the sustainable level of ET from cropping systems that will allow matching of groundwater depletion and recharge.

1. Introduction

The rice-wheat system of north west India is critical for the food security of India. However, as currently practised, large inputs of energy, labour, irrigation water, fertiliser and biocides are required. Cultural practices include intensive tillage for establishment of both wheat and rice, manual transplanting of rice into puddled soil, prolonged periods of ponding during the rice crop, burning of all the rice residues, removal of most of the wheat residues for fodder, and burning of

those wheat residues not removed. The ability to sustain, let alone increase, the productivity of this system is now threatened by a range of environmental and socio-economic factors including: (1) depletion and/or degradation of natural resources (water, soil, biodiversity), (2) low input-use efficiency (especially water, energy, fertilizers, pesticides, labour), (3) environmental pollution (soil, water, air), (4) changing climate, and (5) increasing farm labour scarcity (Hira et al., 2009; Humphreys et al., 2010; Ladha et al., 2007; Yadvinder-Singh et al., 2005) . Therefore, there is a need for technologies which reduce energy, labour and water use, and environmental pollution, and which improve soil physical, chemical and biological properties. Of particular interest is the conversion to conservation agriculture (CA) (Giller et al., 2009; Hobbs et al., 2008; Jat et al., 2012).

Conservation agriculture embodies three major principles – reduced or zero tillage, ground cover at all times, and judicious crop rotation (Hobbs et al., 2008). Conversion of the conventional rice-wheat system to a CA system can be achieved by changing from puddling and manual transplanting of rice to mechanical dry seeding as for crops such as wheat. There is currently much interest in dry seeded rice (DSR) in north west India due to peak period labour scarcity for transplanting, and because puddling and transplanting require large amounts of water to establish the rice crop. Changing to DSR also brings with it the possibility of zero tillage for rice (as well as wheat), and of residue retention on the soil surface instead of burning. Conversion to a CA rice-wheat system offers many potential benefits including greatly reduced tillage and crop establishment costs, timely crop establishment, improved soil structure for wheat, improved nutrient cycling, suppression of soil evaporation and weeds by surface residue retention, reduced energy consumption (and greenhouse gas generation) and groundwater pumping, and reduced air pollution from stubble burning (Balwinder-Singh et al., 2011;

Erenstein et al., 2008; Gathala et al., 2014; Sidhu et al., 2007). Furthermore, the introduction of a short duration legume (mungbean) into the rice-wheat rotation could be beneficial as a break crop for weeds and diseases of the cereal system, as another source of crop residues, and to help meet the shortfall in pulse production in India (Laximpathi Gowda et al., 2013).

The rice-wheat systems of north west India are almost entirely dependent on groundwater pumped from the underlying aquifer (Ambast et al., 2006). However, whether conversion to a CA rice-wheat system would reduce groundwater depletion and increase the productivity of the depleted water has received little attention. Conversion from puddling and transplanting to dry seeding eliminates the need for irrigation for puddling and transplanting, while conversion from continuous flooding to alternate wetting and drying (AWD) water management greatly reduces irrigation requirement after crop establishment for both puddled transplanted rice (PTR) and DSR (Sudhir-Yadav et al., 2011). However, with the same AWD irrigation scheduling, the relative irrigation input to DSR and PTR will depend on many factors, especially infiltration rate in the puddled and non-puddled soil, and crop duration in the main field. While the period from seed to seed is shorter for DSR (because of delayed growth due to transplanting shock in PTR), DSR is in the field for about 3 weeks longer than a transplanted crop, with sowing at a time when evaporative demand is high and frequent irrigation is needed to establish the crop. Direct seeding of wheat into rice residues can reduce the turn-around time between rice harvest and wheat sowing, and thus enable more productive use of residual soil moisture after rice. Furthermore, surface residue retention conserves soil moisture by suppressing soil evaporation. At the same time, it delays the development of wheat in the environment of north west India, increasing crop duration (Balwinder-Singh et al., 2011) and possibly water requirement. Also, with DSR, the window for a legume crop between wheat harvest and rice establishment is shorter than with

PTR. The net effect of all these factors on ET of the total rice-wheat system, and thus on groundwater depletion and the productivity of the depleted water, is not well-understood. Superimposed on this, are the effects of variation in rice variety duration and sowing date, and in seasonal weather conditions. In Part 1, Balwinder-Singh et al. (2014) showed that changing from a long duration to a short duration rice variety greatly reduced ET and irrigation input to a rice-wheat system with conventional farmer crop establishment. However, this came at the expense of total system rice equivalent yield of about 2.5 t ha⁻¹. While addition of mungbean increased system yield by about 3 t ha⁻¹, this came at the cost of increased ET (by about 250 mm) and irrigation requirement (by about 400 mm). None of the combinations of rice variety and sowing date were able to achieve the desired reduction in ET without a substantial loss in cropping system yield.

The above analysis indicates the considerable complexity in examining the effects of replacing a conventional rice-wheat system with a CA rice-wheat system on system yield, components of the water balance and water productivity (WP). Therefore, we used the Agriculture Production System Simulator (APSIM) cropping system model (Keating et al., 2003) to evaluate and compare management options for conventional and CA rice-wheat systems, namely, rice variety duration, rice sowing date, and inclusion of a legume. Comparisons were made in terms of yield, components of the water balance, and water productivity for component crops and for the total system on an annual basis. More specifically, we evaluated: 1) the effects of changing from conventional practice to CA for the rice-wheat system, 2) the effects of inclusion of mungbean in the rice-wheat system, and 3) the tradeoffs between yield, irrigation input, ET, irrigation water productivity (WPI) and ET water productivity (WP_{ET}) for all 4

systems. The ultimate objective was to identify cropping system options with the potential to halt the groundwater decline in north west India, whilst maintaining or increasing system yield.

2. Materials and methods

The APSIM model (v.7.3) was used to explore the impacts of conversion from recommended farmer practice (rFP) using conventional tillage and crop establishment methods to conservation agriculture (CA). The conventional system involved puddled transplanted rice (PTR) grown in rotation with wheat sown after conventional tillage (CTW), with all the rice and wheat residues removed after harvest of each crop. In the CA system, dry seeded rice (DSR) was grown in rotation with wheat in a double zero till (ZT) system with all rice residues and 30% of the wheat residues retained on the soil surface. In both systems, the inclusion of ZT relay sown mungbean in place of the long fallow between the wheat and rice crops was also evaluated. The simulations were performed using 40 years (1970 to 2010) of daily weather data from the meteorological station at Punjab Agricultural University (PAU), Ludhiana. Rice equivalent yield was determined based on the prices paid to farmers for each commodity (grain), as described in Part 1 (Balwinder-Singh et al., 2014).

Performance of the conventional and CA systems was compared in terms of grain yield of individual crops, total system yield (rice equivalent yield), components of the water balance, and water productivity, as outlined in Part 1 (Balwinder-Singh et al., 2014). An overview of APSIM v.7.3 and its parameterisation and evaluation for the rice-wheat system of north west India are also provided in Part 1, with modifications for the CA systems as described below.

In the CA systems, the water holding capacity of the 0-20 cm soil layer was increased by 20% from that of soil in the conventional system. This was done in APSIM by increasing the volumetric water content at saturation (SAT), as long-term addition of crop residues increases

the macroporosity of the top soil layers (Dao, 1993; Franzluebers, 2002; Mulumba and Lal, 2008; Shaver et al., 2002; Singh et al., 2005). The effect of tillage on soil roughness (and thus runoff and water retained on the soil surface available for infiltration) was captured by increasing the USDA curve number from 60 (for zero tillage) to 80 - the number was increased by 10 for discing, and by 5 for each harrowing (Littleboy et al., 1996a,b). The curve number was reset to the default curve number when at least 40 mm of water was added to soil (by rain or irrigation) to simulate the collapse/smoothing of a freshly cultivated soil surface as a result of saturation and rainfall impact. The saturated percolation rate was set to 20 and 6 mm d⁻¹ for non-puddled and puddled soil, respectively, based on the observations of Humphreys et al. (2008) on the same soil.

2.1 Simulations

There were four cropping system scenarios, two of which involved conventional establishment methods - puddled transplanted rice (PTR) followed by conventional tillage and wheat sowing by seed drill (CTW). The other two cropping system scenarios used conservation agriculture practices (CA) in which rice and wheat were sown with a seed drill into non-tilled soil.

2.1.1 Cropping system scenarios

The following four scenarios were compared:

- (i) Recommended farmer practice using conventional tillage and crop establishment (rFP): PTR-CTW-fallow, with no residue retention, as described by Balwinder-Singh et al. (2014)

- (ii) Recommended farmer practice as in (i), but with ZT relay sown mungbean replacing the long fallow between wheat harvest and rice planting (rFP+mung): PTR-CTW-ZTmung
- (iii) Conservation agriculture (CA): ZTDSR-ZTW-fallow, with zero till for both crops and retention of rice and wheat residues (100% of rice residues and 30% of wheat residues)
- (iv) Conservation agriculture with mungbean replacing the long fallow (CA+mung): ZTDSR-ZTW-ZTmung, as for scenario (iii), but with ZT relay sown mungbean (as in (ii)), and retention of all crop residues (100% of rice and mungbean, 30% of wheat)

2.1.2 Simulation variables

For each of the four scenarios, the effects of changing rice sowing date and rice variety duration were evaluated. There were three varieties with long (PR118, 158 d), medium (PAU201, 144 d) and short (PR115, 125 d) duration, and 4 sowing dates at 20-21-d intervals from 15 May to 15 July, as described in Part 1 (Balwinder-Singh et al., 2014).

2.2 Crop management

All crops were grown with nutrients non-limiting in all simulations. Soil nitrogen was reset to original values whenever the nitrogen stress factor for photosynthesis (N_{fact_photo}) fell below 1, by selecting automatic soil nitrogen reset .

2.2.1 Rice establishment

In the conventional system, the soil was flooded 1 d before transplanting and one disking and two tine harrowings were done on the day of flooding. The rice was transplanted using recommended practice - 33 hills m^{-2} with 2 plants $hill^{-1}$ and 25 day-old seedlings as in rFP in Part 1 (Balwinder-Singh et al., 2014).

The DSR was sown at 150 plants m⁻² with a row spacing of 20 cm. However, if there are heavy rains after sowing resulting in waterlogging for a significant period, establishment is impaired as current rice varieties do not have anaerobic germination tolerance. Therefore, a rule was created to reduce plant density according to the duration of ponding after sowing, based on the personal experiences and other observations of the authors. Ponding for 2, 3 or 4 d during the first 5 d after sowing reduced plant density by 15, 40 and 75%, respectively. If ponding occurred for 5 d, the crop was killed and was not resown, to avoid confounding the analysis of the effect of sowing date. In the real world, the farmer would most likely puddle the field and transplant following failed DSR establishment due to waterlogging.

2.2.2 Rice water management

The 40-year simulations commenced with the soil profile full of water at the time of establishment of the first rice crop in 1970. In subsequent years, for DSR, an irrigation of 50 mm was applied on the day of seeding, if needed, i.e. if soil water content was less than the lower limit (LL) in the 0-10 cm soil layer (the usual case, especially for earlier sowings). In PTR, the amount of water applied on the day of puddling was that required to fill the top 3 soil layers (0-30 cm) to saturation plus an additional 50 mm of water to create a surface pond for puddling.

Water management for PTR involved daily topping up to a pond depth of 50 mm for the first 14 d after transplanting, and thereafter irrigating whenever average volumetric water content of the 0-20 cm soil layer had increased to 0.22 cm cm⁻³, equivalent to a soil tension of 20 kPa (estimated from the soil moisture characteristic). In the CA scenarios, the DSR was irrigated whenever volumetric soil water content of the 0-20 cm layer exceeded 0.29 cm cm⁻³ (equivalent to a soil water tension of 10 kPa) from sowing to 25 d after sowing (DAS), after which irrigations were scheduled when volumetric water content of the 0-20 cm soil layer had increased

to 0.22 cm cm⁻³ as for PTR in the rFP scenarios. At each irrigation of both PTR and DSR, the amount of water applied was that required to saturate the 0-30 cm soil profile plus an additional 50 mm of water to create a temporary surface pond. Irrigation of rice in all systems ceased about one week before crop maturity, and the rice was harvested eight days after physiological maturity to allow time for grain moisture content to decline to less than 20%.

2.2.3 Wheat management

Wheat sowing was not permitted before 1 November, regardless of rice harvest date, because early sowing is detrimental to wheat yield. The optimum wheat sowing window for wheat in north-west India is late October- early November, and wheat yield decreases before and after these dates (Ortiz-Monasterio et al., 1994; Timsina et al., 2008). In the rFP system, wheat was sown following rice straw removal and conventional tillage. The rice straw was not removed until six days after harvest, as the residues are still moist and with some green leaves at the time of harvest, and it takes a few days before the straw is dry enough to burn. Straw removal was immediately followed by one irrigation of 75 mm, and four days later tillage commenced (one discing and two harrowings to a depth of 10 mm over a period of five days). The wheat was sown 15 d after rice harvest, but not before 1 November. In the CA systems, the wheat was sown into the rice residues on the day after harvest (or on 1 November when rice harvest was before 31 October) using the Happy Seeder (Sidhu et al., 2007). There was an irrigation of 50 mm on the day of sowing only when the water content of the 0-10 cm soil layer was below the lower limit to ensure good crop establishment. This was always the case in the systems with medium and short duration rice varieties, and also for the 15 May sowing of the long duration variety.

Wheat variety PBW343 (155 d duration) was sown with a plant density of 200 plants m⁻², 20 cm row spacing and 5 cm depth in all systems. The wheat was irrigated whenever soil water

deficit (SWD) increased to 50% in the 0-60 cm soil profile. The amount of irrigation water applied was 120% of SWD and represents a 20% inefficiency of flood irrigation. The wheat was harvested 8 d after physiological maturity to allow time for the grain to dry in the field.

2.2.4 Mungbean management

Mungbean (var. SML668, duration 60 d) was relay sown in both the rFP and CA systems by broadcasting (80,000 plants ha⁻¹) at wheat Zadok's stage 85 (10-12 d before physiological maturity), but not before 20 March (recommended date for summer mungbean in Punjab, Anonymous (2012b)). An irrigation of 60 mm was applied on the day of sowing. Thereafter, the mungbean was irrigated based on 70% SWD of the 0-60 cm soil profile with an irrigation amount equivalent to 120% of SWD. There was no irrigation beyond 55 DAS. The mature mungbean pods were harvested two days before sowing of the DSR, and all the mungbean residues were retained on the soil surface.

3. Results

3.1 Grain yield

Rice yield trends with CA were similar to those with rFP, with only small differences in absolute values (Fig. 1a). For example, with 5 June sowing in the CA system, median yield of the long, medium and short duration rice varieties was 8.0, 7.4 and 5.5 t ha⁻¹ respectively, compared with 7.7, 6.7 and 5.5 t ha⁻¹ with rFP. However, there was one major difference with the last two sowing dates for all varieties - crop failure in a small number of years in the CA system due to untimely heavy rains after sowing of DSR. Rice yields in the rFP+mung and CA+mung systems were very similar to those in the rFP and CA systems, respectively (data not presented).

Trends in wheat yield with CA were also similar to trends with rFP, although the decline in wheat yield with later sowings of the long duration rice variety was less with CA (Fig. 1b),

because of earlier wheat sowing in the CA system. Wheat yields were consistently higher with CA than rFP due to the longer vegetative phase in the CA system as a result of mulching, which led to higher biomass production and more grains m^{-2} . For example, with 5 June rice sowing, median wheat yields with CA were 6.8, 6.6 and 6.6 t ha^{-1} with long, medium and short duration rice varieties, respectively. In comparison, median wheat yields with rFP were 6.6, 6.2 and 6.2 t ha^{-1} , respectively. Wheat yields in the rFP+mung and CA+mung systems were very similar to yields in the rFP and CA systems, respectively (data not presented).

Mungbean yield was highly variable, more so with long duration rice in the CA rotation, and was strongly affected by rice sowing date (Fig. 1c). Mungbean yields were higher in rFP than CA, especially for 15 May sowing, due to the longer window of time available for the mungbean in the transplanted fields than in the dry seeded fields. for the earliest rice sowing date in the CA+mung system, there was usually no or very low mungbean yield because sowing of DSR took place before the mungbean was ready for the first harvest. The reason for zero and low mungbean yields in some years with the June sowings of the long duration variety in the CA system was late rice harvest which delayed wheat sowing, which in turn delayed mungbean sowing.

Trends in rice equivalent yield of the CA rice-wheat system, as affected by rice sowing date and duration, were similar to those for rFP. However, yields of respective sowing date x duration combinations were usually slightly higher with CA than rFP because of the higher wheat yields. For example, with 20 June sowing of the long duration rice variety, average rice-wheat system yields were 12.7 t ha^{-1} and 12.5 t ha^{-1} with CA and rFP, respectively (Table 1a). Yield variability was also higher in the CA than the rFP system for the last 2 sowing dates with medium and short rice varieties, due to establishment failure of the DSR in some years.

Adding mungbean to the rice-wheat system greatly increased rice equivalent yield of both the rFP and CA systems (Table 1a-c), due to the combined effects of the addition of mungbean yield and the much higher price of mungbean than rice and wheat. Yield of the rFP+mung system was higher than yield of the CA+mung system with 15 May sowing of all rice varieties. Highest system yield was with 5 June sowing of the long duration rice variety in both the rFP+mung and CA+mung systems (means 18.0 and 17.7 t ha⁻¹), closely followed by 20 June sowing of the medium duration variety in both the rFP+mung and CA+mung systems.

3.2 Irrigation

Irrigation applications to rice in the CA system were much lower than to rice grown using rFP within respective variety x sowing date combinations (Fig. 2a). For example, median irrigation amount with 5 June sowing of the long duration variety was 730 mm with CA, compared with 975 mm with rFP. Irrigation amount decreased with decrease in varietal duration, more so with the short duration variety in the CA system. For example, with 5 June sowing, median irrigation amount for the long, medium and short duration varieties was 975, 805 and 700 mm, respectively, with rFP. In the CA system, the amounts were 730, 625 and 355 mm, respectively. Irrigation application to rice in the CA+mung system was very similar to that with CA (data not presented).

Irrigation input to wheat in the CA system was often slightly lower than in the rFP system, with maximum median difference of 77 mm with 15 July sowing of the long duration rice variety (Fig. 2b). The higher median irrigation input to wheat in the CA system compared with rFP with 15 May sowing of the long and medium duration rice varieties was partly due to

longer duration of the mulched wheat, It was also partly due to the fact that a pre-sowing irrigation was also needed for wheat in the CA system in 24 out of 40 years due to the long delay between rice harvest and the earliest permissible wheat sowing date (1 November). Irrigation input to wheat in the CA and CA+mung systems was very similar (data not presented).

Median irrigation input to mungbean was around 215 mm, but with lower values for late sowing of the long and medium duration rice varieties in both systems, and for early sowing of these varieties in the CA system (Fig. 2c). The highest irrigation input to mungbean was about 370 mm for both dates in June sowings of all varieties. Irrigation input to mungbean in rFP was higher than in CA (medians higher by 10 to 120 mm within rice variety x sowing date combinations, except for the last sowing of the long and medium duration rice varieties), reflecting the longer growing season made possible by transplanting instead of dry seeding.

Irrigation input to the CA system decreased with decreasing varietal duration, as with the rFP system, however irrigation input was much lower in the CA system (Tables 1a-c). For example, with the long duration variety sown on 5 June, average input was 960 and 1350 mm for the CA and rFP systems, respectively. Average irrigation input with the short duration variety (560 to 640 mm) was only about 60% of that with the long duration variety (960 to 1010 mm) in the CA system. The effect of sowing date on irrigation input to the CA system was less pronounced than with rFP. Variability in irrigation input increased with delay in sowing of the long and medium duration varieties in the CA system, in contrast with the rFP systems, due to failed establishment of DSR in (in 13 and 3 out of 40 years, respectively, for long and medium duration varieties and 15 July sowing). Adding mungbean to the CA system increased irrigation input, with average values increasing by 170 to 300 mm. Irrigation input to CA+mung was much less than to rFP+mung (average values lower by at least 300 mm in respective rice sowing date x

variety combinations) because of the higher irrigation input to both PTR and mungbean in the rFP+mung system. Lowest irrigation input was in the CA system with the short duration rice variety, with similar amounts for all sowing dates.

3.3 Deep drainage

Deep drainage from rice in the CA system was usually lower than drainage in the rFP system (Fig. 3a), because the DSR in the CA system was never ponded (except after heavy rainfall). There was a much smaller effect of rice sowing date on drainage with the long and medium duration rice varieties in the CA system than in the rFP system. The amount of drainage from rice decreased with decrease in varietal duration. However, drainage variability in rice was greater in the CA system due to low drainage in lower rainfall seasons. For example, with 5 June sowing, drainage from rice with the long duration variety ranged from 190 to 740 mm with CA, compared with 390 to 710 mm with rFP (Fig 3a). In years with high and well-distributed rainfall, drainage from rice was higher with CA than rFP due to the higher permeability of the soil in the CA system. Drainage medians from rice in the CA system ranged from 375 to 505, 355 to 460 and 240 to 320 mm for the long, medium and short duration varieties, respectively, compared with 490 to 710, 440 to 620 and 430 to 535 mm with rFP. Adding mungbean to the CA system only had a very small effect on drainage from rice (data not presented).

Drainage from wheat was relatively low in all systems (medians usually less than 20 mm) (Fig. 3b). However, drainage was highly variable, depending on whether there was late rainfall during the rice season. For example, in 1991 there was 100 mm rainfall a few days before rice harvest which left the soil profile quite full to depth, which resulted in higher drainage (128 mm)

during the wheat season. Maximum drainage amounts from wheat ranged from 97 to 141 mm in rFP, and from 55 to 113 mm in the CA system (Fig 3b).

Drainage from mungbean was negligible in all systems in most years, and never exceeded 27 mm (data not presented).

There was never any drainage beyond the root zone during the fallow period between wheat harvest and rice planting for the first two sowing dates in rFP, and median drainage was also very low for the last two sowing dates (Fig. 3c). However, in some years there was significant drainage during the fallow period of up to 150 mm for sowing on 20 June and up to 300 mm for sowing on 15 July because the rainy season started before the end of the fallow period. In contrast, drainage during the fallow period in the CA system was negligible for the first 3 sowing dates, and with very few significant drainage events with the last sowing date, because of the earlier establishment of DSR than PTR. Total drainage during the fallow period between rice harvest and wheat sowing in CA system was negligible except for 15 May and 5 June sowings of the short duration variety, with median values of 80 and 30 mm, respectively, and maximum values of about 300 mm (Fig. 3d). This was because the fallow period after early sown, short duration rice usually started before the end of the rainy season because of early harvesting of rice (23 August to 9 September harvest for 15 May sowing, 10 to 24 September harvest for 5 June sowing of the short duration variety).

Average total system drainage with CA varied from about 330 to 550 mm, compared with higher values of 480 to 830 mm with rFP (Table 1a-c). In both systems there was a trend for slightly lower drainage as rice variety duration decreased, and for higher drainage as rice sowing date was delayed. However, the effect of sowing date was much less in the CA than the rFP

system, and declined to negligible as rice variety duration decreased. Adding mungbean to the system reduced total system drainage with later sowings and longer duration rice in the rFP system, and with very small to negligible reductions in all other treatments (Table 1). Drainage was least with the shortest duration rice variety in the CA and CA+mung systems, with little difference across sowing dates and averages of around 330 mm.

3.4 Evapotranspiration

Trends in rice ET in the CA system were generally similar to those with rFP, except for much lower ET in some years with later sowing in the CA system due to failed establishment because of rain after sowing (Fig. 4a). Rice ET declined with variety duration and to a much lesser degree with delay in sowing. For example, in the CA system, median ET of the long duration rice variety ranged from 720 to 790 mm, compared with 660 to 710 mm for the medium duration variety, and around 460 mm for the short duration variety. Rice ET in the rFP+mung and CA+mung systems was very similar to that in the rFP and CA systems, respectively (data not presented).

Wheat ET was much lower than that of the long and medium duration rice varieties, and similar to that of the short duration variety. Median wheat ET ranged from about 375 to 470 mm across sowing date x variety combinations in both rFP and CA (Fig. 4b). Differences in ET of wheat in rFP and CA were small, although the effect of rice sowing date was smaller in the CA system.

Mungbean ET in the CA system was much less than in the rFP system with the 15 May rice sowing because of the shorter crop duration due to early harvest for sowing of DSR (Fig. 4c). Mungbean median ET ranged from 240 to 325 mm in the rFP system, compared with 155 to

310 mm in the CA system. In the CA system, delaying rice sowing from 15 May to 5 June almost doubled median ET of mungbean from 165 to ~280 mm for all rice varieties, with little change as sowing date of the medium and short duration varieties was further delayed, and a further increase with delay to 20 June sowing of the long duration rice variety.

The magnitude of ET during the fallow between wheat harvest and rice establishment in the rFP and CA systems (Fig. 4d) was less than half of that of mungbean. Fallow ET in both the rFP and CA systems increased as sowing was delayed, much more so in the rFP system because the fallow extended beyond the start of the rainy season. The effect of rice variety duration on fallow ET was very small. Adding mungbean to the system further reduced fallow ET to very low values (medians 1 to 10 mm with the long and medium duration rice varieties, and 2 to 44 mm with the short duration rice variety in the rFP+mung system).

There was a small decline in system ET as rice variety duration decreased, in both the rFP and CA systems (Table 1). In the rFP system, delaying rice sowing usually increased system ET slightly, however, there was very little effect of rice sowing date on ET in the CA system. Addition of mungbean increased system ET within variety x sowing date combinations, usually more so in the CA (averages increased by 140 to 300 mm) than the rFP system (averages increased by 70 to 235 mm, with greater increases as sowing date was delayed). The lowest system ET (averages 965 mm) was with CA using the short duration variety for all sowing dates.

3.5 WPI

Rice WPI with CA (medians usually in the range 2.6 to 16.0 kg ha⁻¹mm⁻¹) was usually much higher than with rFP (medians usually in the range 2.2 to 8.0 kg ha⁻¹mm⁻¹), as a result of lower

irrigation input. Rice variety duration had little effect on WPI in the rFP system, and was also similar for long and medium duration varieties in the CA system (Fig. 5a). However, there was a large increase in WPI with the short duration variety in the CA system in most years. Variability in WPI was also much higher in the CA system, especially for the short and medium duration varieties. WPI was much lower with late sowing of the long and medium duration varieties in both systems due to lower yield from cold damage and death in some years, in model the rice crop was killed when mean daily temperature was below 12°C for 3 consecutive days (Balwinder-Singh et al., 2014) Otherwise, the effect of sowing date on WPI was relatively small. Addition of mungbean to the systems had very little effect on rice WPI (data not presented).

Wheat WPI was more than double that of rice WPI, and often much higher in the CA than the rFP system due to slightly higher yields and slightly lower irrigation amount with CA (Fig. 5b). In both systems, WPI was highest with 5 June and 15 May sowings for all varieties, and decreased with delay in sowing to 15 July, more so as variety duration increased. Median wheat WPI in the CA system ranged from 18 to 36 kg ha⁻¹mm⁻¹, compared with 9 to 18 kg ha⁻¹mm⁻¹ in rFP.

Median values of mungbean WPI were in the range 3.3 to 4.4 kg ha⁻¹mm⁻¹ in the rFP system, and in the range 4 to 6 kg ha⁻¹mm⁻¹ with CA (apart from 15 May rice sowing of all varieties, with much lower values). In the CA system, mungbean WPI followed the same trends as yield, however, this was not the case in rFP as the irrigation input decreased by a greater proportion than yield.

System WPI of all CA systems was generally higher than that of the rFP systems (Table 1). Mean WPI of the CA system ranged from 13.5 to 23.9 kg ha⁻¹mm⁻¹ (excluding the 15 July

sowing of the long and medium duration rice varieties which had much lower WPI) compared with 9.0 to 11.5 kg ha⁻¹mm⁻¹ for the same rice variety x sowing date combinations in the rFP system. The upper 50 percentile values in the CA systems were much higher than in the rFP systems. With both rFP and CA, WPI was considerably lower with the last sowing of the long and medium duration varieties in comparison with the other three sowing dates, due to lower yield. Adding mungbean to the rFP system had little effect on system WPI, apart from slightly reducing variability. Adding mungbean to the CA system greatly reduced variability, especially in the upper 50 percentile.

3.6 WPet

Rice WPet was highest in the CA systems with the short duration variety, with medians of 11.5 to 12.5 kg ha⁻¹mm⁻¹, however, there was a risk of very low or zero yield with the last 2 sowing dates because of establishment failure in a very few years (Fig. 6a). Rice WPet of the long or medium duration varieties was fairly similar in the rFP and CA systems within variety.

Wheat WPet was higher than that of rice. Median values in the CA systems were usually around 15 to 16 kg ha⁻¹mm⁻¹ (the exceptions being the late sown long and medium duration rice varieties), slightly higher than WPet of wheat in the rFP systems (usually around 14 to 15 kg ha⁻¹mm⁻¹) (Fig. 6b).

Mungbean WPet was much lower than that of both rice and wheat, with median values close to 3 kg ha⁻¹mm⁻¹, except with early sown rice in the CA systems, when median WPet was much lower, and zero in some years (12 out of 40 years) (Fig. 6c) due to sowing of rice before the mungbean was mature.

System WPet was higher with CA than rFP within respective rice variety x sowing date combinations due to higher WPet of both rice and wheat in the CA system (Table 1). Addition of mungbean had small but variable effects on WPet, more so with the latest sowing of all varieties in the rFP system. The highest WPet was in the CA+mung system with the short duration variety for June and July sowing dates, with averages of 12.7 to 13.2 kg ha⁻¹mm⁻¹.

4. General discussion

4.1 Evaluation of the performance of APSIM in simulating the effects of rice establishment method

In Part 1 (Balwinder-Singh et al., 2014) we showed that APSIM was well able to simulate the effects of rice sowing date, duration and water management, and of wheat sowing date, in the environment of central Punjab in north west India. Here we focus on the ability of APSIM to simulate the effects of changing establishment method from puddling and transplanting to dry seeding.

The model simulations showed no effect of changing from PTR to DSR on rice yield, and lower irrigation input to DSR than PTR with the same safe AWD water management. These findings are consistent with the findings of field experiments in north west India (Bhushan et al., 2007; Saharawat et al., 2009; Sudhir-Yadav et al., 2011), and of the modeling studies of Sudhir-Yadav et al. (2011; 2012) using ORYZA2000. In the field experiments, the magnitude of the reduction in irrigation amount with DSR compared with PTR with the same AWD irrigation scheduling depended on the weather conditions, especially rainfall. Sudhir-Yadav et al. (2011) found that irrigation input to DSR was lower than to PTR with safe AWD primarily because of the 15 d of continuous flooding after transplanting in PTR, and to a much smaller degree because of reduced

frequency of irrigation of DSR due to reduced soil cracking and thus reduced rate of soil drying. Consistent with this, in the present study, simulated irrigation input during the first two weeks after transplanting was 22% of the total irrigation input to PTR in the rFP system, averaged over the four sowing dates.

Simulated rice ET was similar for PTR and DSR in the rFP and CA systems, respectively. This is to be expected as growth (data not presented) and yield were similar, hence similar ET. Furthermore, soil evaporation (Es) was also similar (data not presented) because with frequent irrigation (irrigation threshold of only 20 kPa), the topsoil remains above field capacity between irrigations, and the next irrigation is applied before Es enters the soil moisture limited stage (stage 2 evaporation). For example, with 15 May sowing of the long duration variety, mean Es during the rice crop was 200 mm (range 165 to 235 mm) in the CA system, and 220 mm (range, 185 to 275mm) in the CA system. In a field study in the same environment, Sudhir-Yadav et al. (2011b) also found similar ET of DSR and PTR irrigated with a 20 kPa irrigation threshold.

4.2 Optimising system performance

The highest average rice equivalent system yield with rFP (14.6 t ha⁻¹) was achieved with 5 June sowing of the long duration variety, followed by 20 June sowing of the medium duration variety (13.8 t ha⁻¹) and 15 May sowing of the long duration variety (13.6 t ha⁻¹) (Table 1). As most farmers sow long duration varieties between 15 May and 5 June, they are already implementing rice-wheat systems with maximum potential yield under current tillage and crop establishment practice. The highest yielding rFP system (5 June sowing of long duration rice) had an average

ET of 1295 mm and an irrigation input of 1350 mm, 45 and 40 mm higher, respectively, than the values for 15 May sowing of the same duration variety. The 5 June sowing had slightly higher WPI (11.3 compared with 10.9 kg ha⁻¹mm⁻¹) and WPet (10.9 compared with 10.6 kg ha⁻¹mm⁻¹) than the 15 May sowing as a result of the higher yield, which more than compensated for the higher ET and irrigation input. Delaying sowing of the long duration variety from 5 to 20 June lowered system yield to 12.5 t ha⁻¹ while increasing irrigation requirement (by 60 mm) and ET (by 20 mm). Concentrating sowing around 5 June would be beneficial in terms of maximizing yield and WPet and minimizing irrigation requirement and ET. However, because of labour limitations, it is not possible for all farmers to transplant all their fields at the same time. In contrast, mechanisation of crop establishment (dry seeding) means that all rice fields can be sown within a much narrower window around the optimum time.

Maximum system yield with CA also occurred with 5 June sowing of the long duration rice variety, with a similar yield (14.5 t ha⁻¹) to that of rFP, but with much lower irrigation input (by 390 mm) due to replacement of PTR with DSR. Conversion to CA also resulted in an average reduction of 55 mm in system ET, a large increase in WPI (from 10.9 to 15.7 kg ha⁻¹mm⁻¹), and a small increase in WPet from (11.3 to 11.7 kg ha⁻¹mm⁻¹).

The highest average system yield (18.0 t ha⁻¹) occurred with the addition of mungbean to rFP with 5 June sowing of the long duration variety. This was slightly higher than yield of the highest yielding CA+mung system (by 0.3 t ha⁻¹), due to the longer period available for mungbean growth between wheat harvest and rice establishment in rFP+mung, as transplanting took place about 3 weeks later than dry seeding. However, this came at the cost of higher irrigation input (by an average of 280 mm) and higher ET (by 260 mm) compared with the highest yielding CA system.

Determination of the optimum cropping system depends on which system performance parameters are to be maximized or minimized, as outlined in Balwinder-Singh et al. (2014). Where land is limiting, the highest yielding system (rFP+mung or CA+mung with 5 June sowing of the long duration rice variety) are the best options for farmers aiming to maximize production. However, if irrigation water is limiting, the best option for farmers aiming to maximize production is systems with the highest WPI (Gaydon et al., 2011). Maximum system WPI occurred when the short duration rice variety was grown in the CA (means 22.0 to 23.9 kg ha⁻¹ mm⁻¹) and CA+mung (means 16.5 to 18.5 kg ha⁻¹ mm⁻¹) systems, with relatively little variation across sowing dates. However, mean system productivity was considerably higher (by 2.8 to 2.9 t ha⁻¹) in the CA+mung system compared with the CA system with the June and July sowings of the short duration variety. These CA+mung systems with short duration rice (yields 15.4 to 15.7 t ha⁻¹) offer the potential to maintain or slightly improve upon the high system yields achievable with conventional practice (rFP system with long duration rice variety and late May/early June sowing), while greatly reducing irrigation input (from around 1330 mm to around 900 mm), and with a significant decrease in ET (from around 1295 mm to around 1200 mm). Such a reduction would go a long way towards improving the groundwater balance if practised on a wide scale, based on the “back of the envelope” estimate of a required decrease in ET of 150 mm of Humphreys et al. (2010). Changing to this system would mean that farmers have to put the effort into growing three crops per year instead of two, the labour and fuel requirements would be greatly reduced because of the conversion to CA. However, there is also the question of the size of the market for mungbean, and whether there are other short duration crops suitable for growing between wheat harvest and rice establishment that could be equally productive/valuable

without increasing ET. In 2010, India imported 3.5 million tons of pulses including mungbean (Laximpathi Gowda et al., 2013).

ET of the cropping system was least with short duration rice in the CA system without mungbean (means of 955 to 975 mm), followed by short duration rice in rFP (means of 1040 to 1150 mm) and CA+mung (means of 1110 to 1255 mm). There was little variation across sowing dates for both yield and ET with short duration rice. Importantly, this provides the option of dry seeding prior to the start of the monsoon, greatly reducing the risk of impaired establishment due to heavy rain after sowing. Furthermore, with early sowing, if there is establishment failure (e.g. due to early rain), there is time for the crop to be re-sown while continuing to practise the CA+mung system without compromising system yield.

The CA system with short duration rice gave large reductions in ET (≥ 300 mm) compared with the highest yielding rFP system, but at the expense of a reduction in average system yield of around 1.5 t ha^{-1} . Short duration rice in the rFP system also gave large reductions in ET (190 to 255 mm), but with larger yield reductions of around 2.5 t ha^{-1} .

Maximum WP_{et} occurred with short duration rice in the CA system (range 12.9 to 13.2 $\text{kg ha}^{-1}\text{mm}^{-1}$ across all sowing dates), and in the CA+mung system for June and July sowings (range 12.4 to 13.2 $\text{kg ha}^{-1}\text{mm}^{-1}$, with values increasing as sowing was delayed). These CA systems had average yields of 12.5 to 12.9 t ha^{-1} ($\sim 2 \text{ t ha}^{-1}$ less than the highest yielding rFP system), but with an average 325 mm less ET. The CA+mung systems had average yields of 15.4 to 15.7 t ha^{-1} , about 1 t ha^{-1} higher than the highest yielding rFP system, and with 45 to 105 mm lower ET. Adoption of these systems on the appropriate proportion of the landscape that enables groundwater depletion and recharge to be balanced would maximize system production of the region. However, restricting the cropped area and requiring a specific cropping

system/management would be unacceptable on socio-economic grounds, difficult to implement, and the magnitude of the permissible cropped area should also depend on how the non-cropped lands are managed as ET from the fallow lands needs to be included in estimating the sustainable cropping area in terms of the regional water balance.

4.3 Significance of the results [

The simulations show that changing from rice-wheat cropping using farmer practice tillage and crop establishment to CA will give large irrigation water savings (among many other benefits). However, it will only go part way towards solving the problem of groundwater table decline as the reduction in ET would be considerably less than required assuming that this is of the order of 150 mm (Humphreys et al., 2010). The only way to achieve this is by the use of short duration rice varieties, regardless of crop establishment method, tillage practice and residue management. This points to the need to focus breeding efforts on raising the yield potential of short duration varieties. The use of alternative crops to rice and wheat should also be considered. However, the simulations of Jalota and Arora (2002) suggest that conversion from rice-wheat to maize-wheat would only reduce ET by an average of 50 mm, while conversion to cotton-wheat would increase ET by 210 mm. Cropping system simulations need to be performed for a range of alternative crops to rice and/or wheat to provide a range of options for reducing ET in comparison with current practice. A pre-requisite for this is good data for parameterising cropping system models for a range of crops and soil types, and for validation of model predictions. Because of the critical importance of reducing ET, there is an urgent need for accurate determination of ET at the farmer field and larger scales, for a range of cropping system options, to validate or fine tune the models. Spatial hydrologic studies are also urgently needed to determine the sustainable level of water depletion from agriculture across the landscape, and for assessment of land use x

management options across the landscape, to identify options for achieving groundwater equilibrium. Such assessment should include biophysical, economic and social criteria.

Cropping system models are based on current knowledge and experience, and take into account interactions between climate, soil, crop and management. Final output largely depends upon the quality of the input parameters (cultivar, soil, and weather), with the dependant variable (often grain yield, or water use) being more sensitive to variation in some parameters than others. To have high confidence in simulation results, the uncertainty for important parameters should be reduced by pertinent calibration and validation (Aggarwal, 1995). The veracity of input parameter values, once calibrated, is confirmed by validating them against a second independent dataset. If the same parameter values used in simulating the calibration dataset also produced acceptable predictions of the dependant variable (normally grain yield, or water use) under independent conditions (the validation dataset), then we consider that the model is validated within the bounds of experimental uncertainty and that the results are at least as trustworthy as conclusions drawn from the experimental results. The results presented here are based on point simulations using only one set of soil physical and hydrological parameters, but there is often large spatial variability for these parameters in farmers' fields. In the present study, some of the soil parameters were from secondary data sources. This includes soil evaporation coefficients, which will effect the soil water balance. We used a single combination of soil-crop-management parameters for each simulation (point simulation) using well calibrated and validated values. For robust evaluation of treatment effects they should be evaluated under different combination of input parameters, particularly where significant uncertainty is judged to exist regarding the value of individual input parameters, either across different farmer's fields, or uncertainties within the one field. The APSIM model does not inherently offer a means of checking how uncertainties

in input parameters flow through to effects on the dependant variable, other than by re-running simulations with values encompassing the uncertainty of possible input parameter ranges and examining the effect on the dependant variable. This method is routinely performed whenever the APSIM model is used.

The work presented here is a unique attempt to use cropping system model simulation to compare conventional practice and CA for a rice-wheat cropping system, focusing on yield, components of the water balance, and water productivity under conditions in which nutrients are not limiting. However, there are many other effects of the conversion. In particular, the lack of tillage and retention of crop residues will have long term effects on nutrient cycling and fertilizer requirement, especially N. APSIM has the capability of simulating the long-term effects of tillage and residue management on N and C dynamics (Probert et al, 1995; 1998). However, lack of data to evaluate the ability of the model to simulate these dynamics in the rice-wheat systems of north west India currently restricts our ability to use the model to look at the overall system. APSIM is a useful tool to study the cropping system characteristics as it has a strong capacity to specify and simulate various management practices. As this study was the first attempt at simulating different establishment methods and CA for irrigated rice-wheat systems in India, we found several areas in the APSIM model which require improvement. These include simulation of the effects of abiotic stresses on rice phenology (water and nutrients), changes in the dynamics of soil physical and hydraulic properties with residue addition and their effects on crop growth and development, seasonal changes in soil hydraulic properties of rice soils as affected by soil and residue management (e.g. puddling versus zero till), and the effect of sowing conditions on DSR germination. We handled some of these deficiencies by manually creating new rules in the model. However, to better understand and incorporate the required science related to these

aspects into the model, targeted field experiments are required to generate the data required for algorithm development and subsequent model validation. Economic evaluation of the cropping system x management options is also needed.

Conclusions

The APSIM model was able to simulate the performance of rice-wheat systems using best practice with current farmer tillage and residue management practice and CA. The main changes in the switch to CA were replacement of transplanting into puddled soil with dry seeding in non-tilled soil, replacement of intensive tillage for wheat with no tillage, and retention of crop residues instead of removal or burning. Current farmer practice is unsustainable for many reasons, including groundwater depletion, which is largely determined by ET in this region where groundwater is the main source of irrigation for rice-wheat systems. The model simulations show that changing to CA alone will not reduce ET. The only way to achieve a substantial reduction in ET is by growing short duration rice varieties in the system. However, this comes at the cost of yield, hence the need for breeders to increase efforts into raising the yield potential of short duration varieties. Intensification to three crops per year in a CA rice-wheat-mungbean system (with short duration rice varieties), has a yield potential slightly higher than that of the highest yielding rice-wheat systems (long duration rice sown in early June, using either rFP or CA), while providing a substantial decrease in ET. This system also has considerable flexibility in rice sowing date, with similar yields for sowings from 5 June to 15 July.

Field experimentation is needed to field test the improved systems as suggested by the model simulations, particularly in terms of cropping system yield and ET, with rigorous

determination of ET using micro-meteorological techniques. Alternatives to rice and wheat should also be evaluated for their impacts on ET and thus groundwater depletion. At the same time, spatial hydrological studies are needed to determine the sustainable level of ET from the cropping system that will allow matching of groundwater depletion and recharge.

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Tables 1a,b,c. Total system yield, components of the water balance and water productivity of conservation agriculture (CA), CA with mungbean (CA+mung), recommended farmers’ practice (rFP), and rFP with mungbean (rFP+mung) as affected by rice variety duration and sowing date in central Punjab, India. Data are mean values, range in parentheses. Mean annual rainfall was 742 mm and ranged from 386-1276 mm over the 40 years. WPi is water productivity based on amount of irrigation water applied and Wpet is water productivity based on ET.

1a. Long duration variety (PR118)

	Rice equivalent yield (t ha ⁻¹)	Irrigation (mm)	ET (mm)	Drainage (mm)	Runoff (mm)	WPi (kg ha ⁻¹ mm ⁻¹)	WPet (kg ha ⁻¹ mm ⁻¹)
15 May Sowing (D1)							
CA	13.9 (10.5-16.4)	971 (680-1580)	1250 (990-1550)	440 (170-755)	50 (0-275)	14.7 (9.1-21.3)	11.1 (9.2-14.5)
CA+mung	14.9 (9.8-18.7)	1180 (890-1800)	1395 (1110-1730)	425 (170-700)	40 (0-172)	12.9 (9.0-16.5)	10.7 (8.0-12.2)
rFP	13.6 (8.8-16.5)	1310 (960-1930)	1250 (950-1610)	520 (380-695)	40 (0-172)	10.6 (7.7-14.2)	10.9 (9.0-13.3)
rFP+mung	16.8 (12.2-20.0)	1490 (1070-2190)	1475 (1170-1810)	461 (290-630)	40 (0-172)	11.4 (8.2-15.3)	11.4 (9.5-13.4)
5 June Sowing (D2)							
CA	14.5 (11.6-17.4)	960 (580-1540)	1240 (980-1515)	450 (190-780)	51 (0-290)	15.7 (9.6-25.2)	11.7 (9.8-14.5)
CA+mung	17.7 (13.7-21.8)	1240 (855-1910)	1500 (1145-1830)	420 (140-740)	40 (0-174)	14.5 (10.2-20.4)	11.8 (10.2-13.5)
rFP	14.6 (10.2-17.5)	1350 (915-1930)	1295 (1020-1630)	550 (420-750)	40 (0-174)	10.9 (7.9-16.4)	11.3 (9.4-13.1)
rFP+mung	18.0 (13.3-21.8)	1700 (1325-2430)	1530 (1245-1810)	495 (320-690)	40 (0-174)	10.7 (7.7-13.5)	11.8 (10.2-13.2)
20 June Sowing (D3)							
CA	12.7 (6.5-17.9)	1010 (190-1375)	1230 (710-1450)	485 (190-745)	46 (0-260)	13.5 (5.7-35.6)	10.3 (5.1-13.9)
CA+mung	15.0 (7.2-22.0)	1280 (465-1730)	1480 (1020-1805)	455 (190-770)	39 (0-200)	12.2 (5.5-24.5)	10.1 (5.2-13.5)
rFP	12.5 (6.4-16.6)	1410 (1155-1770)	1315 (1085-1525)	650 (460-930)	39 (0-200)	9.0 (4.1-13.4)	9.5 (4.9-12.4)
rFP+mung	16.0 (8.7-20.6)	1695 (1350-2195)	1530 (1260-1750)	610 (430-745)	39 (0-200)	9.6 (4.8-13.7)	10.4 (5.9-12.8)
15 July Sowing (D4)							
CA	7.0 (2.3-10.6)	985 (95-1330)	1120 (535-1395)	550 (250-925)	40 (0-235)	10.1 (1.9-65.2)	6.3 (1.9-9.5)
CA+mung	8.5 (5.0-13.2)	1215 (290-1645)	1320 (620-1655)	550 (250-840)	31 (0-180)	7.7 (4.2-26.3)	6.5 (4.0-10.5)
rFP	5.7 (2.5-9.2)	1510 (1110-1765)	1250 (1050-1445)	830 (590-1200)	31 (0-180)	3.7 (1.7-5.4)	4.5 (2.3-6.5)
rFP+mung	8.1 (4.5-12.0)	1650 (1240-2025)	1345 (1100-1595)	715 (565-860)	31 (0-180)	4.9 (2.7-6.5)	6.0 (3.5-7.5)

1b. Medium duration variety (PAU201)

	Rice equivalent yield (t ha ⁻¹)	Irrigation (mm)	ET (mm)	Drainage (mm)	Runoff (mm)	W _{Pi} (kg ha ⁻¹ mm ⁻¹)	W _{Pet} (kg ha ⁻¹ mm ⁻¹)
15 May Sowing (D1)							
CA	14.0 (10.7-16.4)	880 (785-1275)	1185 (935-1370)	405 (175-685)	50 (0-200)	16.3 (10.9-27.8)	11.8 (10.1-13.2)
CA+mung	14.4 (11.2-16.6)	1050 (810-1650)	1335 (1080-1560)	405 (150-630)	40 (0-172)	14.0 (8.8-18.6)	10.8 (9.0-12.2)
rFP	13.0 (8.5-15.6)	1195 (855-1670)	1175 (885-1480)	480 (360-710)	40 (0-172)	10.9 (8.4-15.5)	11.0 (9.3-12.7)
rFP+mung	16.1 (11.5-19.7)	1655 (1290-2245)	1410 (1100-1685)	430 (270-585)	40 (0-172)	9.7 (7.7-12.3)	11.4 (9.5-14.0)
5 June Sowing (D2)							
CA	14.3 (11.1-16.4)	860 (505-1275)	1175 (950-1345)	405 (190-670)	48 (0-260)	17.0 (11.4-27.1)	12.1 (10.5-13.6)
CA+mung	17.1 (13.4-20.2)	1100 (700-1750)	1440 (1205-1635)	395 (135-720)	36 (0-172)	15.9 (10.5-22.5)	11.9 (10.3-13.0)
rFP	13.1 (8.7-15.7)	1180 (869-1640)	1185 (920-1445)	505 (380-690)	36 (0-172)	11.4 (8.8-16.0)	11.2 (9.7-13.3)
rFP+mung	16.4 (11.8-19.7)	1590 (1255-2280)	1390 (1110-1625)	450 (310-650)	36 (0-172)	10.4 (7.8-12.7)	11.8 (9.8-13.6)
20 June Sowing (D3)							
CA	14.4 (7.2-17.8)	890 (190-1255)	1175 (670-1380)	430 (150-705)	45 (0-270)	17.1 (7.2-38.7)	12.2 (5.9-13.9)
CA+mung	17.4 (9.8-21.5)	1125 (405-1635)	1425 (925-1665)	410 (150-655)	37 (0-170)	15.8 (8.1-25.0)	12.2 (6.9-13.7)
rFP	13.8 (9.7-16.8)	1245 (900-1625)	1240 (1015-1440)	575 (380-830)	37 (0-170)	11.3 (9.0-15.8)	11.1 (9.6-12.9)
rFP+mung	17.3 (13.3-20.1)	1585 (1190-2040)	1435 (1135-1640)	530 (335-695)	37 (0-170)	11.0 (8.8-14.2)	12.1 (10.8-13.7)
15 July Sowing (D4)							
CA	9.5 (4.2-16.3)	970 (140-1270)	1165 (620-1430)	490 (210-815)	33 (0-230)	11.4 (5.0-44.1)	8.2 (4.6-12.2)
CA+mung	12.3 (6.7-19.6)	1160 (275-1640)	1380 (550-1625)	465 (210-795)	30 (0-176)	11.4 (6.3-32.7)	8.9 (5.8-12.7)
rFP	8.7 (4.3-12.7)	1355 (1000-1640)	1245 (1055-1450)	730 (545-970)	30 (0-176)	6.5 (3.4-10.4)	7.0 (3.9-10.0)
rFP+mung	11.1 (6.7-15.6)	1585 (1215-1895)	1320 (1105-1580)	625 (465-770)	30 (0-176)	7.1 (4.6-11.1)	8.4 (5.8-12.2)

1c. Short duration variety (PR115)

	Rice equivalent yield (t ha ⁻¹)	Irrigation (mm)	ET (mm)	Drainage (mm)	Runoff (mm)	WPI (kg ha ⁻¹ mm ⁻¹)	WPet (kg ha ⁻¹ mm ⁻¹)
15 May Sowing (D1)							
CA	12.5 (9.8-15.5)	610 (300-1115)	970 (820-1190)	350 (75-635)	40 (0-200)	22.0 (12.0-39.0)	12.9 (11.4-12.2)
CA+mung	12.9 (9.7-15.4)	805 (490-1230)	1110 (940-1325)	360 (105-660)	22 (0-200)	16.5 (11.3-23.6)	11.6 (9.1-13.1)
rFP	11.9 (8.8-14.2)	1130 (830-1560)	1060 (800-1370)	510 (330-710)	22 (0-200)	10.6 (8.2-13.4)	11.2 (9.3-13.1)
rFP+mung	15.0 (11.0-18.3)	1590 (1185-2135)	1295 (1030-1600)	440 (265-610)	22 (0-200)	9.5 (7.6-12.3)	11.5 (9.9-14.4)
5 June Sowing (D2)							
CA	12.7 (10.0-15.6)	560 (270-910)	955 (710-1150)	330 (65-660)	45 (0-170)	23.9 (14.2-41.2)	13.2 (11.6-14.6)
CA+mung	15.6 (12.2-18.9)	860 (590-1275)	1255 (980-1460)	320 (25-670)	34 (0-170)	18.5 (13.2-23.7)	12.4 (10.7-13.8)
rFP	11.8 (8.2-14.2)	1040 (675-1510)	1040 (780-1305)	490 (365-655)	34 (0-170)	11.5 (8.7-17.5)	11.4 (9.3-13.1)
rFP+mung	15.0 (11.1-18.0)	1380 (1000-1915)	1245 (975-1495)	415 (250-585)	34 (0-170)	10.9 (8.4-13.3)	11.9 (10.1-14.4)
20 June Sowing (D3)							
CA	12.5 (7.4-15.6)	575 (215-945)	960 (710-1150)	335 (140-665)	50 (0-220)	23.5 (11.8-56.2)	13.0 (7.3-14.7)
CA+mung	15.4 (10.1-18.9)	860 (465-1255)	1210 (905-1425)	320 (90-645)	41 (0-160)	18.3 (10.5-29.2)	12.7 (8.3-14.1)
rFP	11.9 (7.3-14.4)	1035 (710-1510)	1075 (835-1285)	530 (400-775)	41 (0-160)	11.5 (8.6-16.6)	10.9 (8.7-12.6)
rFP+mung	15.0 (11.1-18.0)	1310 (905-2005)	1225 (920-1460)	465 (315-630)	41 (0-160)	11.6 (8.4-15.1)	12.1 (10.3-14.2)
15 July Sowing (D4)							
CA	12.9 (4.8-16.1)	640 (95-930)	975 (555-1160)	360 (130-660)	45 (0-225)	22.2 (14.3-67.2)	13.0 (8.7-14.5)
CA+mung	15.7 (6.2-19.4)	930 (290-1270)	1190 (620-1430)	365 (95-655)	35 (0-110)	17.3 (14.0-26.1)	13.2 (9.9-14.2)
rFP	12.3 (8.7-15.4)	1165 (865-1500)	1150 (960-1310)	640 (460-855)	35 (0-110)	10.8 (8.4-14.4)	10.8 (8.7-13.0)
rFP+mung	15.0 (11.3-18.6)	1420 (1140-1870)	1220 (990-1415)	540 (320-745)	35 (0-110)	10.5 (8.6-12.9)	12.2 (11.1-13.9)

Figure

Figs 1a-c. The effect of rice sowing date (D1-D4) and rice variety duration (long, medium, short) on yield in rice-wheat systems using recommended farmers' practice (rFP) or conservation agriculture (CA). Yield of rice (a), wheat (b), mungbean (c). Vertical shaded bars are 5-95 percentiles, black dots show the range and triangle represents median values over 40 years (1970-2010). Sowing dates are 15 May (D1), 5 June (D2), 20 June (D3), 15 July (D4).

Figs 2a-c. The effect of rice sowing date (D1-D4) and rice variety duration (long, medium, short) on irrigation input in rice-wheat systems using recommended farmers' practice (rFP) or conservation agriculture (CA). Irrigation input to rice (a), wheat (b), mungbean (c). Vertical shaded bars are 5-95 percentiles, black dots show the range and triangle represents median values over 40 years (1970-2010). Sowing dates are 15 May (D1), 5 June (D2), 20 June (D3), 15 July (D4).

Figs 3a-d. The effect of rice sowing date (D1-D4) and rice variety duration (long, medium, short) on drainage below the root zone (180 cm) in rice-wheat systems using recommended farmers' practice (rFP) or conservation agriculture (CA). Drainage from rice (a), wheat (b), fallow after wheat harvesting (c), after rice harvesting) (d). Vertical shaded bars are 5-95 percentiles, black dots show the range and triangle represents median values over 40 years (1970-2010). Sowing dates are 15 May (D1), 5 June (D2), 20 June (D3), 15 July (D4).

Figs 4a-d. The effect of rice sowing date (D1-D4) and rice variety duration (long, medium, short) on ET in rice-wheat systems using recommended farmers' practice (rFP) or conservation agriculture (CA). ET from rice (a), wheat (b), mungbean (c), the long fallow between wheat harvest and rice planting (d). Vertical shaded bars are 5-95 percentiles, black dots show the range and triangle represents median values over 40 years (1970-2010). Sowing dates are 15 May (D1), 5 June (D2), 20 June (D3), 15 July (D4).

Figs 5a-c. The effect of rice sowing date (D1-D4) and rice variety duration (long, medium, short) on irrigation water productivity (WPI) in rice-wheat systems using recommended farmers' practice (rFP) or conservation agriculture (CA). WPI of rice (a), wheat (b), mungbean (c). Vertical shaded bars are 5-95 percentiles, black dots show the range and triangle represents median values over 40 years (1970-2010). Sowing dates are 15 May (D1), 5 June (D2), 20 June (D3), 15 July (D4).

Figs 6a-c. The effect of rice sowing date (D1-D4) and rice variety duration (long, medium, short) on ET water productivity (WPet) in rice-wheat systems using recommended farmers' practice (rFP) or conservation agriculture (CA). WPet of rice (a), wheat (b), mungbean (c). Vertical shaded bars are 5-95 percentiles, black dots show the range and triangle represents median values over 40 years (1970-2010). Sowing dates are 15 May (D1), 5 June (D2), 20 June (D3), 15 July (D4).