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Simulation of resource-conserving technologies on productivity, income and greenhouse gas GHG emission in rice-wheat system

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The Rice-wheat (RW) cropping system is one of the major agricultural production systems in four Indo-Gangetic Plains (IGP) countries: India, Pakistan, Bangladesh and Nepal of South Asia covering about 32% of the total rice area and 42% of the total wheat area. The excessive utilization of natural resource bases and changing climate are leading to the negative yield trend and plateauing of Rice-wheat (RW) system productivity. The conservation agriculture based efficient and environmental friendly alternative tillage and crop establishment practices have been adopted by the farmers on large scale. A few tools have been evolved to simulate the different tillage and crop establishment. In the present study, InfoRCT (Information on Use of Resource Conserving Technologies), a excel based model integrating biophysical, agronomic, and socioeconomic data to establish input-output relationships related to water, fertilizer, labor, and biocide uses; greenhouse gas (GHG) emissions; biocide residue in soil; and Nitrogen (N) fluxes in the rice-wheat system has been validated for farmer participatory practices. The assessment showed that double no-till system increased the farmer's income, whereas raised-bed systems decreased it compared with the conventional system. The InfoRCT simulated the yield, water-use, net income and biocide residue fairly well. The model has potential to provide assessments of various cultural practices under different scenarios of soil, climate, and crop management on a regional scale.

Key words: Biocide residue index, global warming potential, greenhouse gas emission, nitrogen budget, resource conserving technologies, rice-wheat system; systems analysis.

INTRODUCTION

South Asia covers 22% of world population on less than 5% world land area with diverse eco-regions, land and management practices. Rice-wheat (RW) cropping system is one of the major agricultural production systems, which is source of livelihood, employment and income for hundreds of millions of rural and urban poor of South Asia (Ladha et al. 2003). The RW system (RWS) occupies 24-26 million ha (M ha) in Asia (Jing et al., 2010), mainly with 13.5 M ha in the Indo-Gangetic Plains (IGP), covering about 32% of the total rice area and 42% of the total wheat area in four IGP countries. Lately there

has been a negative yield trend and plateauing of RW system productivity as well as in yield leading excessive utilization of natural resource bases (Pathak et al., 2003). The productivity and sustainability of the RW system in the IGP is threatened because of (i) the efficiency of current production practices; (ii) the scarcity of resources, especially water and labour, and associated changes in land use; (iii) climate change; and (iv) socio-economic changes. Thus, the region's food security is threatened by these emerging challenges of natural resource degradation rising population and climate change.

Farmers in this region usually grow rice in the wet (monsoon) season after intensive dry and wet tillage (puddling) followed by wheat in the dry (winter) season after intensive dry tillage. Therefore, multiple tillage

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operations; and contrasting edaphic requirements for rice and wheat create problems in timeliness of wheat seeding, maintenance of soil structure, and management of irrigation, weeds and other pests, and crop residues (Saharawat et al., 2011, Gathala et al., 2011a). Moreover, timely labour availability and increasing labour costs are serious concerns for the timely planting of crops. In the IGP, as well as in many other parts of Asia, water is increasingly becoming scarce (Gleik, 1993) because of increasing competition from the urban and industrial sectors (Seckler et al., 1998; Toung and Bhuiyan, 1994). The growing labor and water shortages are likely to adversely affect the productivity of the RW system (Gathala et al., 2011a; Jat et al., 2009; Saharawat et al., 2009; Ladha et al., 2003). In the changing climatic conditions, the increased night temperature at flowering stage causes spikelet sterility in rice and a reduction in yield of about 5% per degree Celsius rise above 32°C. Therefore, conventional RW practices need future transformation to produce more food at higher income levels and reduced risk; more efficient use of land, labour, water, nutrients, and pesticides than at present; mitigation of greenhouse gas (GHG) emissions; and adaptation to climate change (Jat et al., 2011; Pathak et al., 2011, Saharawat et al., 2011).

Conservation agriculture (CA)-based resource conservation technologies (RCTs) including new cultivars are more efficient, use less input, improve production and income, and address the emerging problems (Gupta and Seth, 2007; Saharawat et al., 2010). The RCTs involving no- or minimum-tillage with direct seeding, and bed planting, innovations in residue management to avoid straw burning, and crop diversification are being advocated as alternatives to the conventional RW system for improving productivity and sustainability (Sharma et al., 2002; Barclay, 2006, Ladha et al., 2009). There is a need for wider scale testing of these new technologies for water, labour and energy efficiency in farmers managed trails. Long-term field trials to study these efficiencies will be time consuming, costly and some of the parameters such as nitrogen flux, biocide residue and green house gases are difficult to measure, hence modeling approach is desirable for quantitative evaluation of RCTs.

Computer-based simulation modeling and management information systems are useful tools for assessing the complex interactions between a range of factors, including climate, soil and management, that affect crop performance. Crop models can assist in the impact assessment and future extrapolation potential of improved technologies. The InfoRCT (Information on Use of Resource Conservation Technologies), a programmed in Microsoft Excel containing various parameters organized in different worksheets. The InfoRCT model was generated on evaluation of RCTs from a long-term experiment in western IGP (Pathak et al., 2011). The model helps to extrapolate the impact of RCTs on yield, income, nitrogen (N) budget, and green house gas (GHG) emissions in different scenarios of soil and climatic

conditions and crop management (Pathak et al., 2011). The present study was carried out in farmers managed participatory approach to evaluate and validate the effects of various RCTs on productivity, resource (water, labour and energy) use efficiency, cost effectiveness and environmental impact that is, N loss, GHG emission and biocide residue in soil in RW system of the IGP.

MATERIALS AND METHODS

Site characteristics

On-farm evaluation of RCTs was carried out on randomly selected seventy six RW growing farmers from ten villages in four districts (Karnal, Kurukshetra, Kaithal and Yamunanagar) of Haryana, India (29°07'15" N to 30°08'15" N, 75°02'20"E to 77°04'10"E) (Figure 1). The mean annual rainfall of the study area varies from 650 mm to 970 mm and about 80% of which is received in June to September. The minimum and maximum temperature varies from 4°C to 46°C. The soils are generally sandy loam to clay loam in texture and low to medium in organic matter content. Groundwater pumping is the pre-dominant method of irrigation. Haryana state is predominantly a RW growing area where wheat is grown by broadcasting after six to seven dry tillage operations and rice seedlings (3-4 weeks old) are transplanted in puddled fields after four to five dry tillage operations.

Initially a baseline survey of randomly selected farmers from different villages was conducted to understand their social, economical, educational status in addition to the input use (seed, irrigation, tractor, labour, fertilizer, and pesticides use) and output (grain and straw yield) in the conventional farmer practice (FP, T1) that is, traditionally tilled puddle transplanted rice followed by broadcasted wheat on tilled soil. The farmers were introduced to the alternative tillage and crop establishment methods that is, T2). Unpuddled-transplanted rice (UP-TPR) followed by no-till drill seeded wheat (ZTW). T3). Transplanted rice on raised beds (BP-TPR) followed by no-till drill seeded wheat on same beds (ZTW). T4). No-till transplanted rice (ZT-TPR) followed by no-till drill seeded wheat (ZTW). T5). No-till dry-direct-drill-seeded rice (ZT-DSR) followed by no-till drill seeded wheat (ZTW). Details of soil, water and crop management practices followed in rice and wheat have been reported elsewhere (Saharawat et al., 2010; Bhushan et al., 2007). All the farmers used no-till drill seeding in wheat but tillage and crop establishment methods in rice differed among the farmers (Table 1) according to their field conditions. Conventional farmers practice (FP) of RW growing was compared with alternate tillage and crop establishment method at the each farmer's field. Details of each farm operation were recorded and analyzed for input use and all agronomic practices at each farmer's field.

Seeding and seed rate

The field operations for DSR and growing rice (cv Sarbati) nursery were initiated from last week of May to first week of June, whereas, transplanting was done from mid June to end of June. Sowing dates for DSR and nursery were kept same under different management practices. 20 to 30 kg ha⁻¹ primed rice seed (soaking seeds in water for 8 h followed by over night air drying) were seeded at a depth of 2-3 cm using seed-cum-fertilizer drill whereas 10-15 kg ha⁻¹ seed was used for transplanting. Wheat (cv PBW 343) was seeded in from the first to last week of November with a seeding rate of 80-120 kg ha⁻¹ with seed-cum-fertilizer drill. The drills were calibrated every time before seeding to adjust the seeding rate.

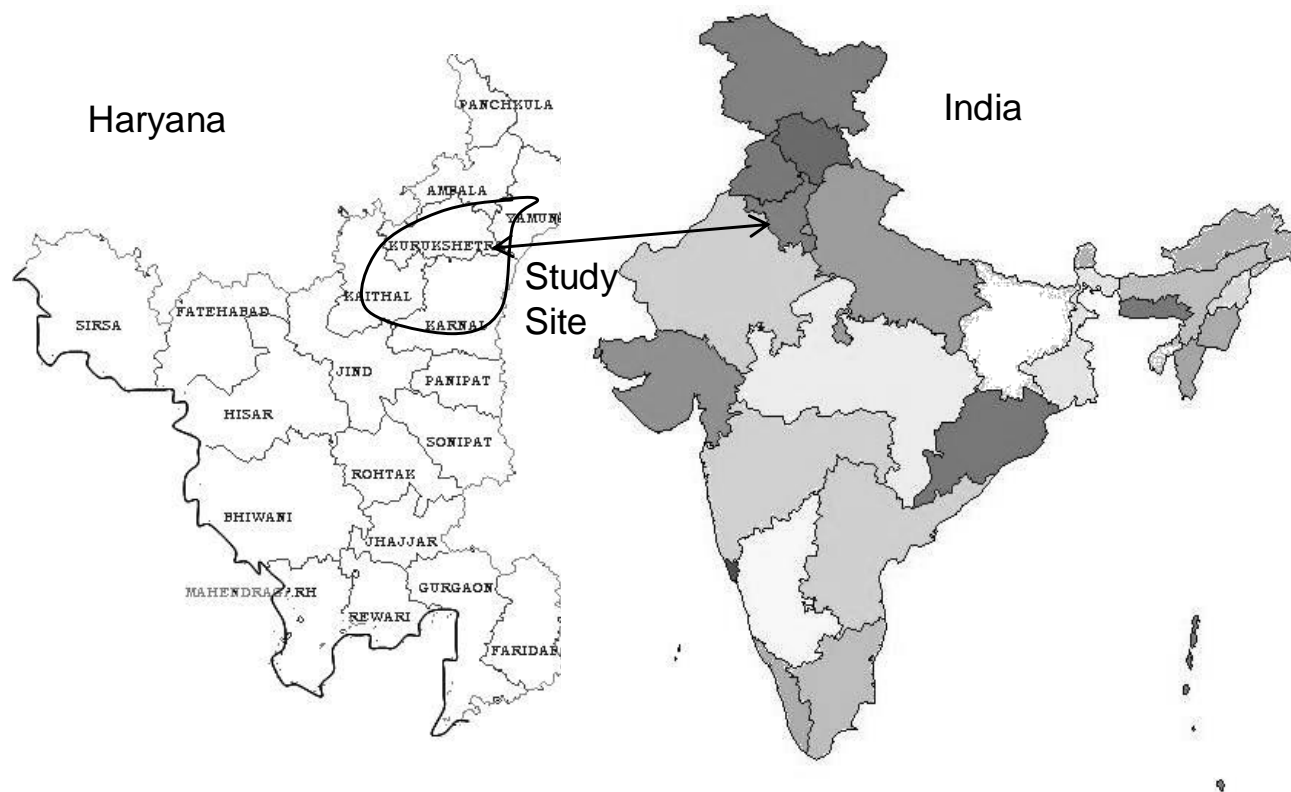


Figure 1. Location of the experimental sites in Haryana, India.

Table 1. Description of tillage and crop establishment methods in rice-wheat system.

Treatment	Rice	Wheat	Number of farmers
T1	Transplanted rice after conventional puddling (FP),	Broadcasted wheat after Conventional tillage (FP)	76
T2	Transplanted rice in unpuddled fields (UP-TPR)	Drill sown wheat after zero tillage (ZTW)	41
T3	Transplanted rice on raised beds (BP-TPR)	Drill sown wheat on same beds after reshaping (ZTW)	9
T4	Transplanted rice after zero tillage (ZT-TPR)	Drill sown wheat after zero tillage (ZTW)	6
T5	Direct-drill-seeded rice after zero tillage (DSR)	Drill sown wheat after zero tillage (ZTW)	20

Water application and measurements

Flooding method of irrigation was followed by each farmer in the study area. The discharge of each tubewell was measured using a water meter (Dasmesh Co. India). Time required for each irrigation was recorded in each treatment. The quantity of water applied and the depth of irrigation were computed using the following equations:

$$\text{Quantity of water applied (L)} = F * t \quad (1)$$

$$\text{Depth of water applied (mm)} = (L/A)/1000 \quad (2)$$

Where, F is flow rate ($L s^{-1}$), t is time (s) taken during each

irrigation, and A is area of the plot (m^2).

Rainfall data were recorded from the nearby observatory. The total amount of water applied was computed as the sum of water received through irrigation and rainfall.

Fertilizer application

Farmers fertilizer application varied from 130-160 kg N, 0-60 kg of Phosphorus(P) and 0-60 kg potassium (K) ha^{-1} in rice and 140-190 kg N, 0-50 kg P and 0-60 kg K ha^{-1} in wheat in all the practices. While K was broadcasted for rice, N (80% of the total quantity) and

whole of P was placed at 10-cm depth using no-till seed-cum-fertilizer drill at the time of seeding in DSR (T5). In transplanted rice N (80% of the total quantity) and whole of P, K fertilizers were broadcasted by some farmers before transplanting. Extra dose of N was applied on the basis of leaf colour chart (LCC) as described by Shukla et al. (2004). For wheat, all the fertilizers were applied basally using no-till seed-cum-fertilizer drill.

Weed management

All the farmers kept their fields weed free either by using herbicides or hand weeding. Pre-seeding germinated weeds in no-till fields (DSR and ZT-TPR) were controlled by glyphosate @ 900 g ai. ha⁻¹. In DSR, pre-emergence weeds were controlled by applying pendimethalin @ 1 kg ai. ha⁻¹/ pretilachlor plus safener @ 480 g a.i. ha⁻¹ within 48 h of sowing, followed by post-emergence herbicides as chlorimuron ethyl + metsulfuron methyl (Almix, DuPont, Wilmington, DE) @ 4 g ai. ha⁻¹ at 20-25 days after sowing (DAS). In transplanted rice, butachlor @ 1.5 kg ai. ha⁻¹ was applied at 2 days after transplanting (DAT) to control the weeds by some farmers but mostly preferred the hand weeding. In wheat crop, grassy weeds were controlled by spraying sulfosulfuron @ 35 g ai. ha⁻¹ at 20-25 DAS, and broadleaf weeds were controlled using 2,4-D @ 500 g ai. ha⁻¹ at 30-35 DAS.

Labour and machine use

Human labour use for tillage, seeding, irrigation, fertilizer and pesticide application, weeding, and harvesting in rice and wheat were recorded during each operation. Time (h) required to complete one field operation was recorded and expressed as person-day ha⁻¹, considering 8 h to be equivalent to 1 person-day. Similarly, time (h) required by a tractor-drawn machine to complete a field operation such as tillage, seeding, fertilizer application and harvesting was recorded and expressed as h/ha. Time (h) required irrigating a field as well as diesel consumption (1 ha⁻¹) by the pump was also recorded. In case of electric pumps electricity charges were included as per the state electricity board.

Economic analysis

The cost of cultivation was calculated by taking into account cost of seed, fertilizers, biocide, and the hiring charges of human labor (US\$ 2.4 d⁻¹) and machine (US\$ 5.7 h⁻¹) for land preparation, irrigation, fertilizer application, plant protection, harvesting, and threshing, and the time required per hectare to complete an individual field operation was recorded. Cost of irrigation was calculated by multiplying time (h) required to irrigate a particular plot, consumption of diesel by the pump (1 h⁻¹) and cost of diesel (US\$ 0.76 l⁻¹) and electricity rates were as per the state electricity board. The prices of human, machine labor, and diesel were taken as per the Government of India norms. Gross income was the minimum support price offered by the Government of India for rice (US\$ 127.1 Mg⁻¹) and wheat (US\$ 125.1 Mg⁻¹). Net income of the farmers was calculated as the difference between gross income and total cost. System productivity was calculated by adding the grain yield of rice and wheat in each year.

Statistical analysis

As farmer participatory trials were conducted in many villages within a district. Sometime field of farmer for comparative study was a bit apart in these trials. Therefore, we considered the farmer as a block as field used in study was of same farmer. The block (farmers)

effect on yield and yield parameters of rice and wheat, water use efficiency, and economics were analyzed with IRRISTAT for Windows for one-way analysis of variance (ANOVA). Duncan's multiple range test (DMRT) was used at the P<0.05 level of probability to test the differences between the treatment means. Unless indicated otherwise, differences were considered significant only when P<0.05.

Crop and resource modelling

The InfoRCT (Information on Use of Resource Conservation Technologies), a Microsoft Excel based model, integrates bio-physical, agronomic and socio-economic data to establish input-output relationships in rice-wheat system under different tillage and crop establishment methods. The data in the worksheets 'site', 'crop', 'price', 'labour' and 'biocide' are region-specific, reflecting natural conditions as well as current practice of farmers. The worksheets 'technologies' and 'resource balances' contain generic information. The worksheet can easily be amended if other technologies are assessed or more technical coefficients should be computed. The spreadsheet model works on target yield based approach (Figure 2) and can be adopted for quantitative evaluation of the RCTs in terms of productivity, resource use efficiency, cost effectiveness and environmental impact that is, N loss, GHG emission and biocide residue in soil. Conventional farmers' practice data from the farmer participatory trials was used as the model input data to calculate the required amounts of fertilizer, irrigation water, biocides, human and machine labor, and seeds as well as N budget, biocide residue, and GHG emissions in RW system under various RCTs. The climatic data was recorded from the nearest possible weather station. Using the primary data, InfoRCT model was validated for the fertilizer requirement (N, P, K), irrigation water requirement, N losses, GHG emission and biocide residue index under different RCTs adopted by the farmers using the target-oriented-approach (Pathak et al., 2011).

Modelling efficiency (ME)

$$ME = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (3)$$

where O_i and S_i represent the observed and simulated values, n represents the number of observed and simulated values used in the comparison, and \bar{O} the observed average:

$$\bar{O} = \sum_{i=1}^n \frac{O_i}{n} \quad (4)$$

One is considered to be the best modelling efficiency. Negative values of modelling efficiency are considered as unacceptable (Ghulam et al., 2004).

RESULTS AND DISCUSSION

Experimental

Yield of rice-wheat system with various technologies

In addition to tillage and crop establishment practices

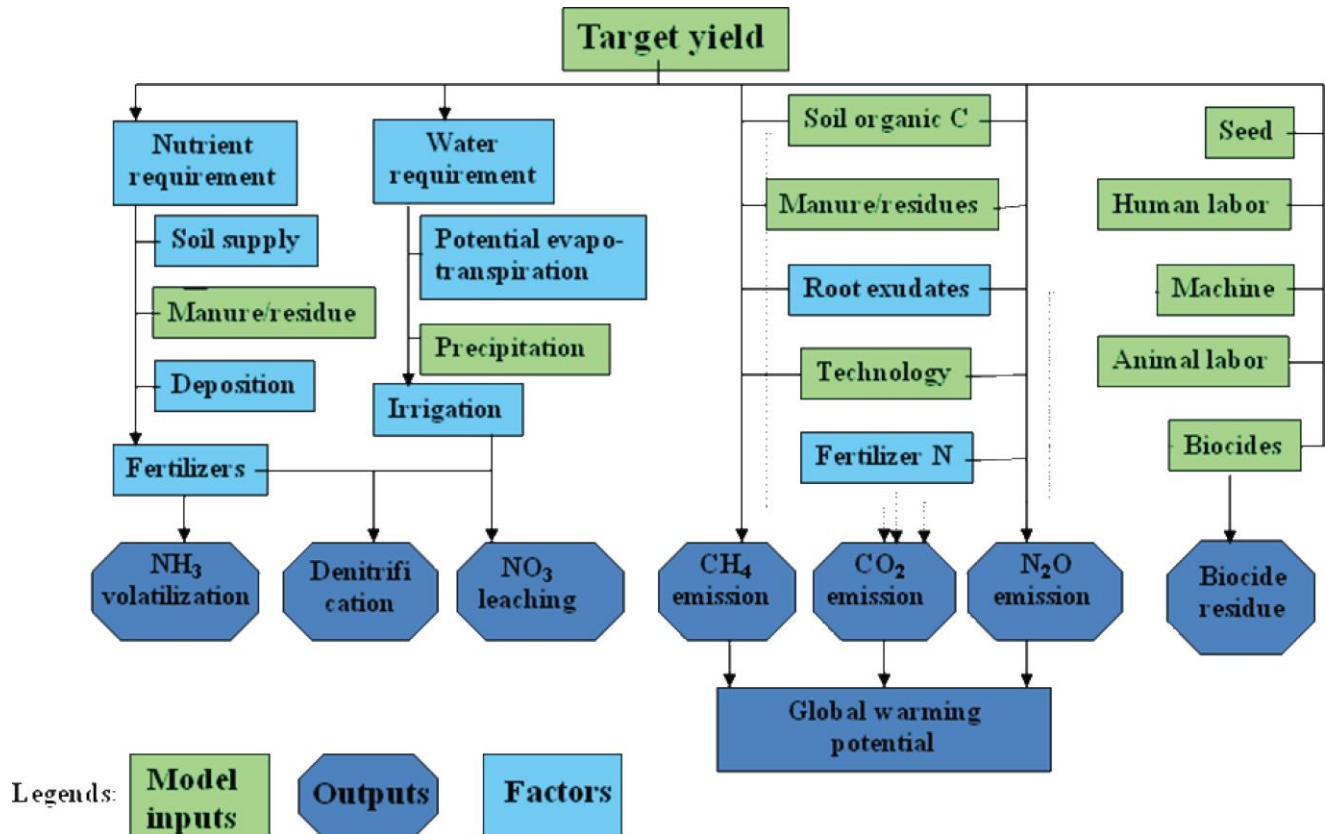


Figure 2. Figure 1. Relational diagram of the InfoRCT decision support system.

distribution of rainfall had an effect on the rice yield in both years. Rice yields were higher during year 2 as compared to year 1 (Table 2 and Figure 3) due to favorable distribution of rainfall that is, more rains at particular intervals during the crop establishment (Figure 4). Rice yield in UP-TPR (T2) and ZT-TPR (T4) was higher or on a par with conventional puddled transplanted (T1) (Figure 3). In ZT-TPR (T4), 75% of the farmers had a yield increase of 0.85 Mg ha^{-1} followed by 0.75 Mg ha^{-1} in UP-TPR (T2). In raised bed transplanted rice (T3), 75% farmers had a yield loss of 0.42 Mg ha^{-1} followed by 0.1 Mg ha^{-1} in DSR (T5) (Figure 3). On an average, highest rice yields (6.6 and 6.8 Mg ha^{-1}) were obtained in unpuddled transplanting (T2) followed by zero-till transplanting (T4) and FP (T1). In DSR (T5) yields were 3 to 5% lesser than ZT-TPR (T4), UP-TPR (T2) and FP (T1). This showed that water and labour intensive operation of puddling can be avoided without yield penalty in rice. Rice transplanted on raised beds (T3) yielded 11 and 9% lower in year 1 and 2 respectively, than in conventional method (T1). Transplanted rice on beds (T3) suffered from water stress compared to when planted on flat land resulting in lower yields. Earlier published research have shown higher panicles in per square meter in DSR than in TPR and higher spikelet sterility in DSR on unpuddled soil than TPR (Saharawat

et al., 2010; Bhushan et al., 2007; Choudhary et al., 2007) Moisture stress at critical stages (panicle initiation and flowering) has been observed to cause a yield reduction in rice by lowering the number of grains per panicle and increasing spikelet sterility (Nieuwenhuis et al., 2002; Belder et al., 2002; Lu et al., 2001), consequently yield of aerobic rice is generally lower than submerged rice (Gathala et al., 2011b; Saharawat et al., 2009; Pinheiro et al., 2006). Likewise, other researchers have reported a rise in soil pH, salt accumulation, and Iron (Fe) deficiency in rice grown on raised beds (Sharma et al., 2002; Yadvinder et al., 2008). Zero-till or reduced-till transplanting not only yielded better, it also had saving in labor, time, water and energy, and thus cost (Kumar and Ladha, 2011; Saharawat et al., 2010). Direct drill-seeded rice has another advantage; decreased growth duration by 7 to 10 days allows timely planting of succeeding wheat (Saharawat et al., 2009, Rashid et al., 2009; Bhushan et al., 2007; Balasubramanian and Hill, 2002).

In contrast to rice, wheat yield was 3-4% higher on raised beds (T3) in year 1 and 2. In no-till wheat 75% farmers had a yield increase of 0.75 Mg ha^{-1} on raised beds (T3) followed by 0.61 Mg ha^{-1} after ZT-TPR (T4) and 0.50 Mg ha^{-1} after UP-TPR (T2) and DSR (T5) than FP (Figure 3). These results are in agreement with earlier

Table 2. Grain yield Mg ha⁻¹ in rice (R)-wheat (W) system with different tillage and crop establishment practices in Haryana, India.

Technology	Grain yield (mg ha ⁻¹)					
	2005-06			2006-07		
	R	W	R+W	R	W	R+W
T1	6.4					
T2	6.6	4.8	11.4	6.8	4.8	11.6
T3	5.7	4.8	10.5	5.9	4.8	10.7
T4	6.4	4.8	11.2	6.5	4.8	11.3
T5	6.2	4.8	11.0	6.2	4.8	11.1

studies (Jat et al., 2011, 2009; Kumar et al., 2008). Bhushan et al. (2007), who found that the performance of wheat is not much affected at least in short-term by the way the previous rice crop is grown.

Rice + wheat (system) yields were similar in puddled transplanted (T1), unpuddled transplanted (T2), no-till transplanted (T4) and direct drill seeded (T5) treatments, but on raised beds (T3) yield was 5% lower than in T1. In double no-till system, 61% of the farmers had a system yield gain of 1.5 Mg ha⁻¹ and 0.5 Mg ha⁻¹ over T1 respectively (Figure 3). Yield loss of 0.43 Mg ha⁻¹ was recorded in raised-bed system (T3) (Figure 3). Similar yield trends were observed in both the years. Unpuddled transplanting followed by ZT wheat (T3) gave higher system yields than conventional (T1) and double no-till system (T4 and T5). Earlier studies have revealed that bed planting may be useful in poorly drained soils, as wheat is sensitive to poor aeration (Sharma et al., 2003), but for good drained soils as in the present study, bed planting system needs further improvement (Bhushan et al., 2007; Gathala et al., 2011b).

Water application and use efficiency

The irrigation water application depends on the total rainfall and its pattern of distribution. In year 2 higher amount of irrigation was applied due to less rainfall (Figures 4 and 5). On average highest water application was in UP-TPR (T2; 2680 mm) due to the high infiltration rate followed by conventional puddled transplanted (T1; 2620 mm) and ZT-TPR (T4; 2515 mm) (Figure 5). In UP-TPR (T2), 56% of farmers applied more irrigation water (204 mm ha⁻¹) than conventional puddle transplanted rice (T1). In ZT-TPR (T4), 52% farmers applied 226 mm ha⁻¹ more irrigation water and 25% farmers applied 278 mm ha⁻¹ less water. In DSR (T5), 79% farmers applied 172 mm ha⁻¹ less water and 18% applied 81 mm ha⁻¹ more irrigation water than conventional puddle transplanted rice. Minimum water was applied in raised-bed system (T3), 25% farmers applied 375 mm ha⁻¹ less water and 75% applied 215 mm ha⁻¹ less than T1 (Figure 5). Water application in DSR (T5) was 7 to 8 % less than the T1.

Earlier studies have shown that alternate-wetting and drying leads to improvement in rice yields by improving the oxygen status of the root zone (Uphoff and Randriamiharisoa, 2002), however the effect is site-specific and depends on soil type and groundwater depth (Bouman et al., 2002; Bouman and Tuong, 2001). Bhushan et al. (2007), and Jat et al. (2005), also reported a saving of 7 to 10% in irrigation water under DSR. Transplanting on raised-bed (BP-TPR, T3) resulted in 16 to 18% less water application than the FP (T1). Bhushan et al. (2007) have also reported a 13-23% saving in irrigation water on raised beds but with parallel yield reductions. Irrigation water applied to wheat ranged from 380 to 448 mm depending on amount of rainfall, and tillage and crop establishment methods in two years. The RCTs have no effect on the water application in wheat in both the years.

Input use (Biocide, labour and machine)

The alternative tillage and crop establishment methods had major influence on biocide, mostly herbicide, use in rice (Table 3). In the transplanted system irrespective of crop establishment method (T1, T2, T3 and T4) biocide use was 14.5 kg ai. ha⁻¹, which increased to 22.5 kg ai. ha⁻¹ in DSR (T5) because of more weed infestation. Weed is a major challenge in DSR has been reported in earlier studies (Saharawat et al., 2009; 2010; Bhushan et al., 2007; Singh et al., 2007, 2005a), leading to heavy use of herbicides or intensive hand weed control (Rao et al., 2007; Singh et al., 2005b). Biocide use for wheat was small (2.5 kg ai. ha⁻¹) compared to rice and was similar in all the treatments (Table 3).

Conventional puddled transplanted rice (T1) and BP-TPR (T3) had the highest machine use (14.1 h/ha and 14.6 h/ha) followed by unpuddled transplanted rice (T2), no-till transplanting (T4) and least (5.0 h/ha) in DSR (T5) (Table 3). The conventional-till wheat (T1) had 10% higher machine use per hectare in comparison to all other treatments. The higher machine use in farmer practice was due to intensive tillage before planting of both rice and wheat.

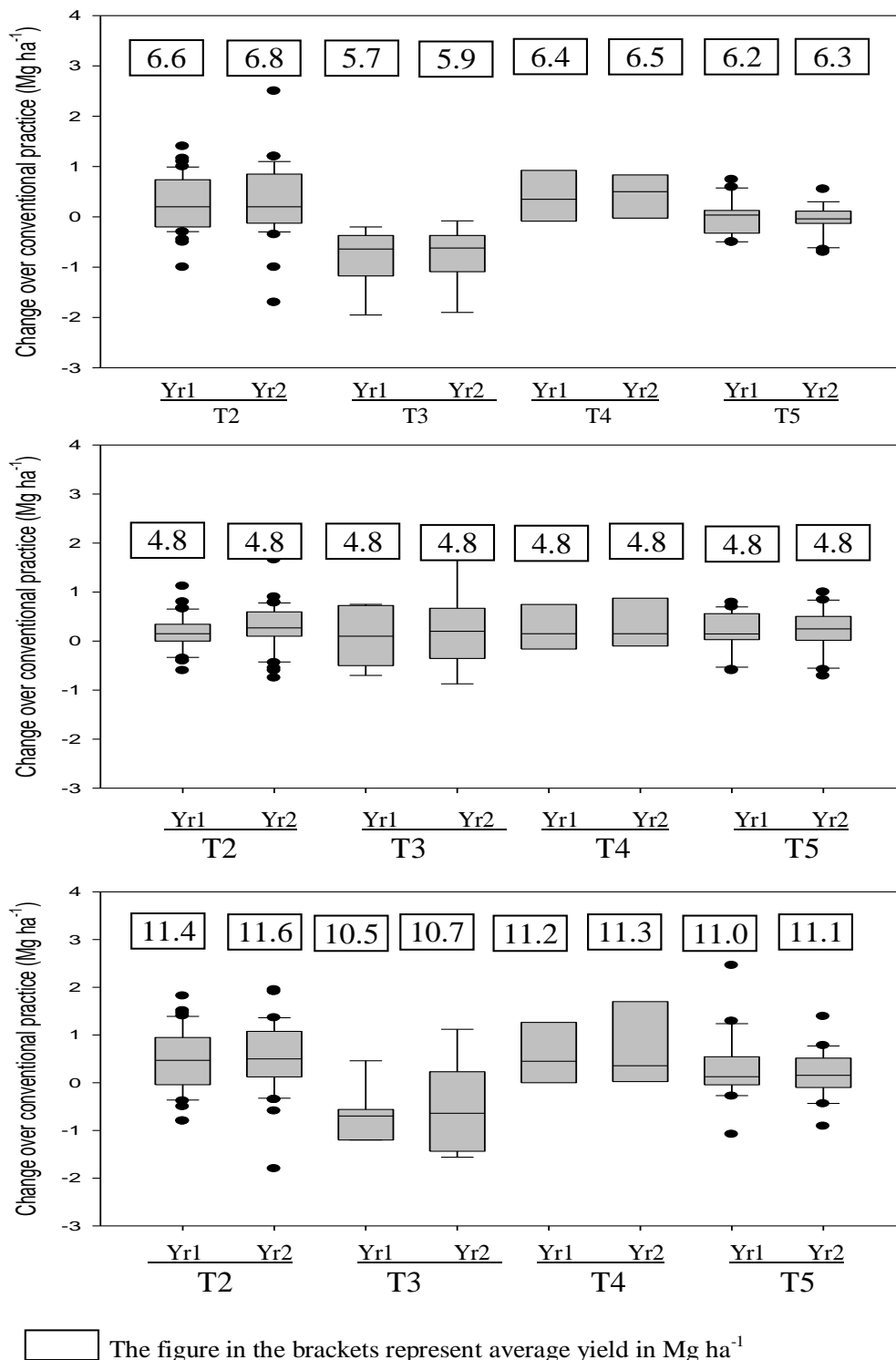


Figure 3. Yield Change of rice, wheat and system over the conventional practice (T1) in various tillage and crop establishment methods.

Labour use was lowest in ZT-TPR (T4) (57 days ha⁻¹) followed by DSR (T5) and raised-bed transplanting (T3) (ranging from 60-66 days ha⁻¹). In T1 and T2, labour use

was high due to larger human labour needed for transplanting of rice and tillage operations (Table 3). Least labour requirement was in double ZT system due to no

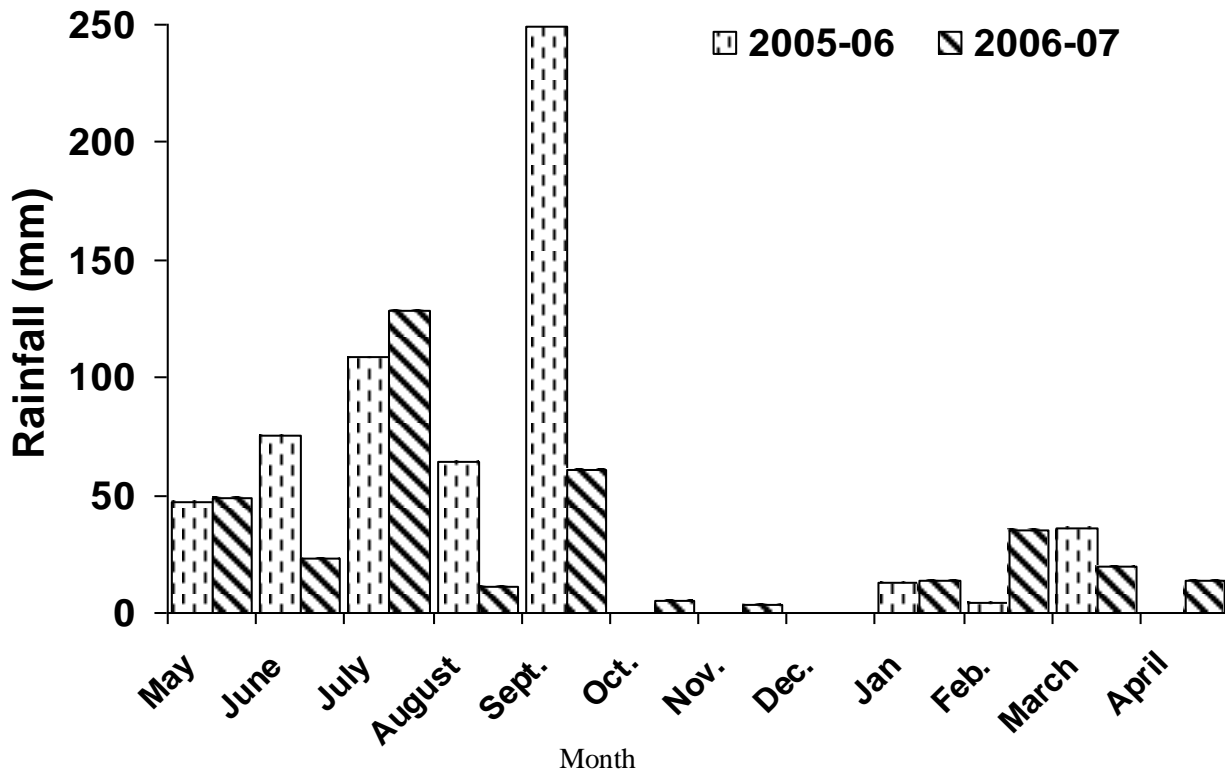


Figure 4. Rainfall pattern during the crop season in 2005-2007.

tillage operations. In wheat, human labour requirement was same (14 days ha⁻¹) in all the treatments except in the FP (T1), which needed 2 labour-day more (16.0 days ha⁻¹) for tillage operations. Earlier studies have also reported a saving of machine, labour and energy by avoiding the puddling operation in rice (Gathala et al., 2011a; Jat et al., 2011; Saharawat et al., 2009, 2011, Kumar and Ladha, 2011).

Economic analysis

Net returns (mean for 2 years) in wheat were much higher compared to rice largely because of less irrigation cost (Table 4). In rice, the largest return (US\$ 313 ha⁻¹) was obtained DSR (T5) followed by UP-TPR (T2). Savings in DSR (T5) ranged from US\$ 28 to 67 ha⁻¹ (mean of US\$ 49 ha⁻¹) over FP (T1). The savings were mainly through reduced cost in land preparation (77%), irrigation water (15%) and labour (8%). Rice on raised beds (T3) had the lowest returns (US\$ 214 ha⁻¹) due to low yields. In wheat, raised beds (T3) and no-tillage (T2, T4 and T5) had higher net returns than the FP (T1). On a system basis, the return (US\$ 674 ha⁻¹) was maximum in the DSR (T5) followed by UP-TPR (T2) and double no-till system (T4) and the least was in the bed planting systems (US\$ 578 ha⁻¹).

Validation of InforCT model

Yield, water application and economic analysis of rice-wheat system

A fairly good correlation was obtained in observed and simulated yield of rice (ME = 0.78) and wheat (ME = 0.86) (Fig. 6a, b). In rice, simulated yields were generally higher than observed yields except in raised bed transplanting (T3), where yields were predicted 13 to 18% lower. Moreover the simulated grain yields in all treatments and in both rice ($r^2=89^{**}$) and wheat ($r^2=92^{**}$) were significantly correlated (Figures 6a and b). The observed and simulated irrigation water application had a good correlation in rice (ME = 0.45) (Figure 6c) except that the simulated values for water use in rice on raised beds (T3) were significantly very low as compared to the observed values. Simulated irrigation water use in rice was fairly correlated ($r^2=77^{**}$) in all treatments. Fairly good correlation (ME = 0.81) was observed in irrigation water use in wheat in all the treatments. The irrigation water application in wheat ($r^2=86^{**}$) was significantly correlated (Figure 6d). The simulated net income showed a fairly good correlation with the observed net income in rice (ME = 0.87) and ($r^2=99^{**}$) (Figure 6e) in all the treatments. Poor correlation existed in observed and simulated net income in wheat crop (ME = 0.38) and

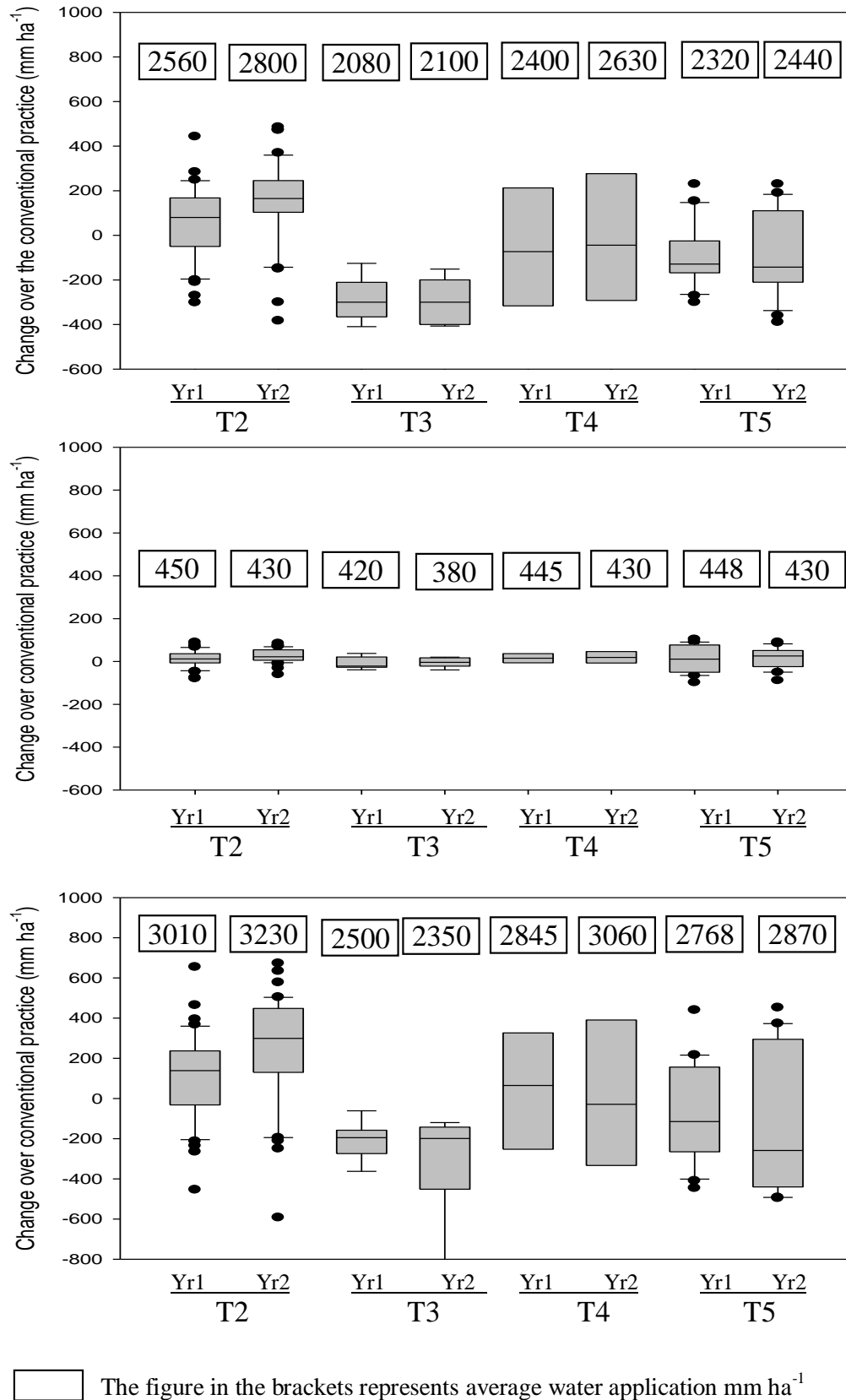


Figure 5. Water application change in rice, wheat and system over the conventional practice (T1) in various tillage and crop establishment methods.

Table 3. Calculated biocide, machine and labour use in rice (R)-wheat (W) system with different tillage and crop establishment practices in Haryana, India.

Technology	Biocide (kg ha ⁻¹)						Machine labor (h/ha)						Human labor (d ha ⁻¹)					
	2005-06			2006-07			2005-06			2006-07			2005-06			2006-07		
	R	W	R+W	R	W	R+W	R	W	R+W	R	W	R+W	R	W	R+W	R	W	R+W
T1	14.5	2.5	17.0	14.5	2.5	17.0	14.1	11.5	26	14.0	11.5	26	63	16	79	66	16	82
T2	14.5	2.5	17.0	14.5	2.5	17.0	12.3	6.5	19	12.0	6.5	19	64	14	78	68	14	82
T3	14.5	2.5	17.0	14.5	2.5	17.0	14.6	6.5	21	11.0	6.5	18	60	14	74	66	14	80
T4	14.5	2.5	17.0	14.5	2.5	17.0	7.5	6.5	14	7.0	6.5	14	57	14	71	57	14	71
T5	22.5	2.5	25.0	22.5	2.5	25.0	5.0	6.5	12	5.0	6.5	12	60	14	74	64	14	78

Table 4. Observed and simulated net income in rice-wheat system with different tillage and crop establishment practices in Haryana, India.

Treatment	Observed net income (US \$)			Simulated net income (US \$)		
	R	W	R+W	R	W	R+W
T1	264±22 †	357±5	621±31	231±18	388±11	618±16
T2	287±14	358±8	645±20	244±24	428±20	672±23
T3	214±6	364±7	578±10	181±11	434±21	615±14
T4	279±11	360±7	639±18	237±14	375±11	612±28
T5	313±26	361±5	674±23	272±22	440±24	712±20

† ± represents Standard deviation

($r^2=23^{**}$) (Figure 6f) due to differences in irrigation water, tillage operations and grain yield of farmers. Earlier studies have shown a fairly good correlation between observed and simulated yield, water application and net income using InfoRCT (Pathak et al., 2011, Saharawat et al., 2011), using RIWER modeling framework (Jing et al., 2010), using ceres-wheat and ceres-rice (Timsina and Humphreys, 2006), and APSIM (Balwinder et al., 2011) in rice-wheat system of South Asia.

Simulation using InfoRCT

Emission of greenhouse gases

Simulated CH₄ emission in rice ranged from 25 to

59 kg ha⁻¹, and the FP (T1) had the largest emission followed by unpuddled transplanting (T2) (Table 5). Emission of N₂O from soil in rice as well as in wheat varied between 0.10 and 0.12 kg N₂O-N ha⁻¹. Fertilizer contributed 0.24 and 0.37 kg N₂O-N ha⁻¹ in rice while it was between 0.42 and 0.54 kg N₂O-N ha⁻¹ in wheat (Table 5). Farm machinery including pump used for irrigation emitted 389 to 507 kg CO₂-C ha⁻¹ in rice and 58 to 81 kg CO₂-C ha⁻¹ in wheat. Off-farm practices such as production of fertilizer contributed 117 to 199 kg CO₂-C ha⁻¹ in rice and 222 to 252 kg CO₂-C ha⁻¹ in wheat. Production of biocides contributed 47 to 82 CO₂-C ha⁻¹ in rice, while its contribution was negligible in wheat. Application of fertilizer and biocide contributed about 40 kg CO₂-C ha⁻¹ i

rice-wheat system. Contribution of soil to CO₂ emission was taken as zero as organic C remained more or less static for the last 4-5 years in this present study. Several other long-term fertility experiments in rice-wheat cropping systems in northwest India also showed static organic C (Ladha et al., 2003). Different RCTs in rice-wheat system had pronounced effects on the GWP, which varied between 2799 kg CO₂ equivalent ha⁻¹ in raised-bed system (T3) and 3286 CO₂ equivalent ha⁻¹ in FP (T1). Compared to the FP (T1) all the technologies reduced the GWP by 3 to 28% (Figure 7). Previous studies using the InfoRCT model have also reported similar results (Pathak et al., 2011, Saharawat et al., 2011) under different tillage and crop establishment practices

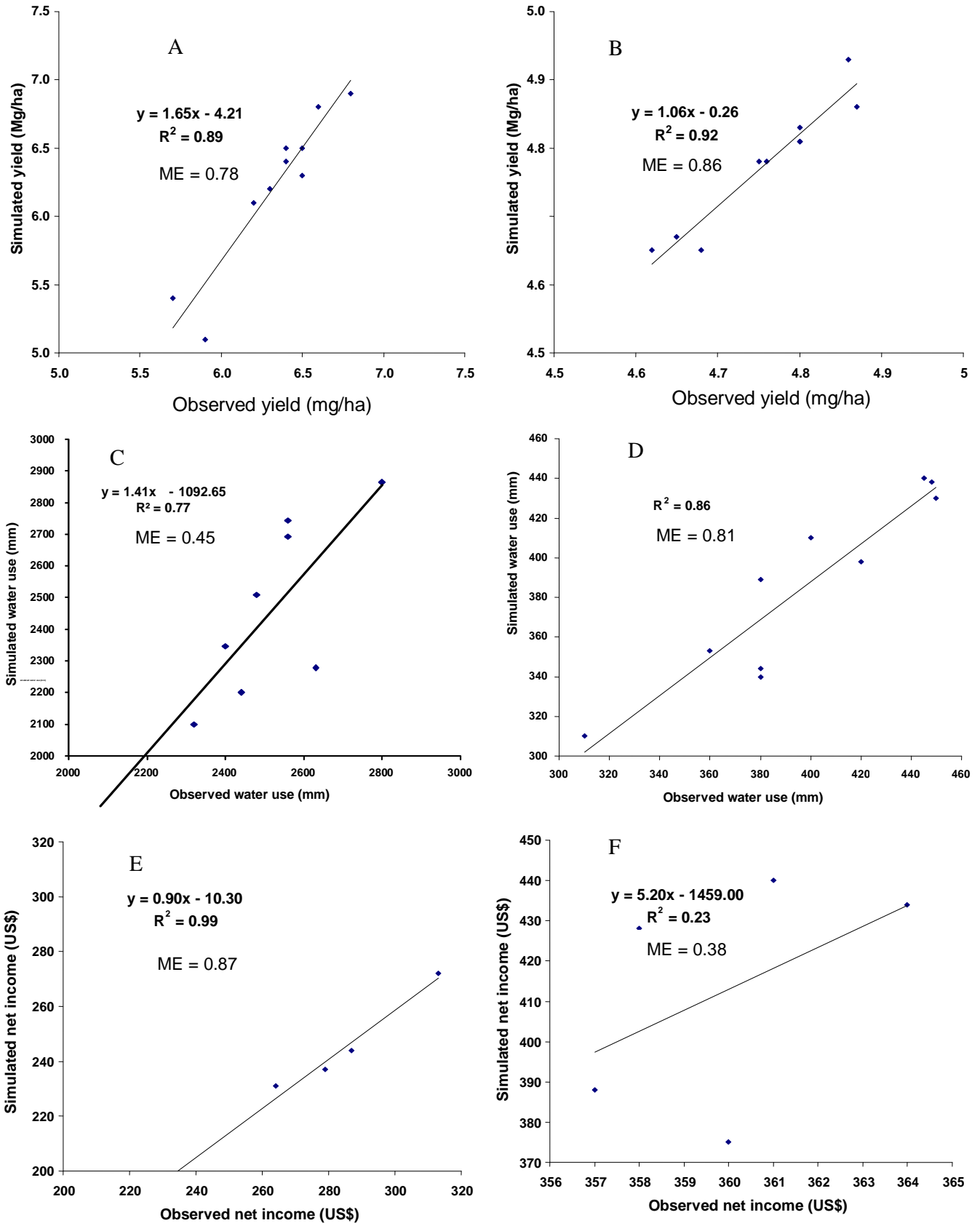


Figure 6. Simulated and observed grain yields, water use and net income by rice (a,c,e) and wheat (b,d,f) respectively in various tillage and crop establishment practices .

Table 5. Simulated greenhouse gas emissions in rice-wheat system with different tillage and crop establishment practices in Haryana, India.

Technology	Crop	CH ₄ soil kg ha ⁻¹	N ₂ O soil (kg N ha ⁻¹)	N ₂ O fertilizer (kg N ha ⁻¹)	CO ₂ machine (kg C ha ⁻¹)	CO ₂ fertilizer produce (kg C ha ⁻¹)	CO ₂ biocide produce (kg C ha ⁻¹)	CO ₂ fertilizer application (kg C ha ⁻¹)	CO ₂ biocide application (kg C ha ⁻¹)	GWP {(CO ₂ equi) (kg ha ⁻¹)}
T1	Rice	59	0.10	0.32	478	199	47	11	11	3286
	Wheat	0	0.10	0.42	81	256	0.2	14	0	597
	RW	59	0.20	0.74	559	455	47	25	11	3884
T2	Rice	48	0.11	0.36	507	197	47	10	11	3174
	Wheat	0	0.11	0.47	66	256	0	14	0	576
	RW	48	0.23	0.83	573	454	47	24	11	3750
T3	Rice	25	0.12	0.24	389	117	82	6	18	2209
	Wheat	0	0.12	0.53	60	261	0	14	0	591
	RW	25	0.24	0.77	450	378	82	19	18	2799
T4	Rice	25	0.12	0.37	446	182	69	9	15	2491
	Wheat	0	0.12	0.46	59	222	0	11	0	542
	RW	25	0.24	0.83	505	404	70	21	15	3033
T5	Rice	25	0.12	0.41	433	202	82	10	18	2482
	Wheat	0	0.12	0.54	58	222	0	10	0	564
	RW	25	0.24	0.95	501	466	82	25	18	3046

in the RW system.

Conclusion

The on-farm evaluation of RCTs show that unpuddled or no-till transplanting practices gave highest rice productivity (6.6 and 6.8 Mg ha⁻¹). On the other hand, wheat yields were not affected by tillage and crop establishment methods in shorter

term. Rice had substantial yield loss on raised beds. On the rice-wheat system basis, except raised-bed system, other tillage and crop establishment methods had similar yields. However, in overall performance parameters (grain yield, water productivity, irrigation water use and benefit/cost), no-till transplanting and DSR were the best. Hence no-till and unpuddled system was the best for resource management. The InfoRCT Model could simulate the effects of RCTs on yield, income, emission of GHGs in rice-

wheat system satisfactorily. The model will help to extrapolate the impact of RCTs on yield, income, N budgets and GHG emission across the South Asia in different scenarios of soil and climatic conditions and crop management. This approach will benefit to scientists, planners, policy makers, agricultural practitioners, environmentalists, and the farmers for predicting the impact of new and emerging crop management technologies, making decision relating to resource use, and designing strategies for improved crop production.



Figure 7. Simulated global warming in various tillage and crop establishment practices of rice and wheat.

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