Conservation agriculture for improving water productivity in Vertisols of semi-arid tropics

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Large variability and uncertainty of rainfall are the main limiting factors for crop growth in rainfed agriculture. Agriculture water management interventions are considered as suitable adoption strategy to enhance crop yield, productivity and income in rainfed condition. Three-year experimental data collected at the International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India are analysed to study the impact of *in-situ* interventions (tillage and crop residue) on field water balance and grain yield under the two different cropping systems (maize + chickpea sequential and maize/pigeon pea intercropping). One dimensional water balance model is calibrated to capture field hydrology (soil water, surface runoff). Weather data calibrated for 36 years showed that incorporating crop residues reduced surface runoff by 28% compared to control fields. However, the impact of tillage and residue treatment on soil water was not consistent throughout the growing period. Water productivity values for intercropping systems (WUE = 0.61 to 1.49 kg m^{-3}) were relatively higher compared to sequential cropping systems (WUE = 0.47 to 1.06 kg m^{-3}). Second crop in sequential cropping system often suffered from water stress that led to poor crop yield. However, a few rain events at the end of the monsoon period were beneficial to second crop. Simulation results indicated that the conservation agriculture could save up to 30% yield loss incurred due to water stress during deficit rainfall compared to conventional agricultural practices.

Keywords: Conservation agriculture, crop residue, minimum tillage, rainfed agriculture, semi-arid tropics, soil water balance, Vertisols.

Introduction

CONSERVATION agriculture (CA) is an important *in situ* intervention considered for practicing resilient and climate-smart agriculture. The three basic components of CA are: (i) zero or minimum tillage, (ii) retention of crop residues on the soil surface and (iii) crop diversification. Minimal tillage reduces volume and velocity of surface runoff, leading to reduction in soil erosion and nutrient loss; incorporation of crop residues enhances soil water availability, reduces evaporation loss[1–3], improves infiltration by restricting surface runoff and reduces surface sealing from raindrop impact[3]. Crop diversification reduces the risk of crop failure and is recognized as a cost-effective solution to build resilience into agricultural production system[4,5]. Diversification also brings stability in soil fertility through cultivating legumes with cereals in rotation or intercropping system[6,7].

Recent studies have reported that CA improved crop productivity by 20–120% and water productivity by 10–40% (refs 8–12). On farm trials showed[8] that the CA not only improved the crop yield, but also generated higher gross returns compared to farmers' practice. However, other studies reported no improvement or at some cases negative effects on crop yield by adopting such techniques[13,14]. For example, a meta-regression analysis on CA trials in Europe indicated 0–30% decrease in the crop yield as compared to conventional practices[14]. A general argument is that in addition to CA, appropriate farming practices such as timely planting, balanced nutrient management, crop protection and weed management are necessary to improve crop productivity.

The rainfed agriculture in the semi-arid tropics (SAT) is typically characterized by low crop yields and high risk of crop failure. Frequent dry spells and extreme rain events are the most common characteristics of SAT, which often cause water stress situation and land degradation during rainy season[15]. Important factors influencing soil water dynamics are soil characteristics and climate[16,17]. In India, one fourth of the semi-arid region is covered by Vertisols. These soils have characteristic mineral (smectite) that causes swelling and shrinkage of the soil during wetting and drying events[18]. Infiltration rate when the soil is dry can be as high as 76 mm h^{-1}, though the bypass/preferential flow through cracked Vertisols may be much higher. In fact, undisturbed cracks under no-till practices are beneficial to redistribute the water in deeper soil layers[19]. Wider and deeper cracks partially expose sub-surface layers to atmosphere and increases evaporation[20,21]. A significant portion of green water stored in vadose zone may be lost from the system which subsequently could affect the crop water availability and groundwater recharge negatively in the following rainy season.

This article presents results of three-year CA trial conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India.

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The objective of this study was to identify the yield potential of CA trials based on soil water dynamics. CA practices including minimum tillage and incorporation of crop residues were compared with conventional farming practices under two different cropping systems. Observed runoff volume, soil water content and total grain yield were used to simulate the impact of CA practices on *in situ* water conservation and crop productivity. Modelling and simulation exercise comprise: (i) modification of soil water balance model to incorporate effects of CA practices in Vertisols, (ii) development of production function for grain yield as a function of relative reduction in evapotranspiration and (iii) long-term impact of CA practices on crop yield and runoff using simulated soil water balance and estimated grain yield.

Materials and methods

Site description

Field experiments were conducted on experimental watershed at ICRISAT (17.50°N 78.26°E and altitude 545 m). Soil at the experimental site is medium black and clayey (Vertisols). Depth-wise distribution of physical and chemical properties of soil is shown in Table 1. The local climate of the study area is semi-arid with average rainfall of 898 mm, of which about 781 mm rainfall distributed over June to October (*kharif* season) and about 87 mm distributed over November to April (*rabi* season). Maximum and minimum temperature may reach up to 43°C and 5°C during May and December respectively. Average wind speed during *rabi* season remains below 2 m s^{-1}, which may reach up to 5 m s^{-1} during *kharif* season.

Field experiments

Field layout of a micro-watershed for field experiments is shown in Figure 1. The watershed is divided into two parts by a grassed water channel, which carries runoff from both sides. Watershed has gentle slope of less than 1% (represented by dotted arrows in Figure 1). The field trials were laid out in a split–split plot design with two tillage methods as main treatments: normal tillage and minimum tillage, two sub-treatments of crop residues: no residues retention and retention of all crop residues, and two sub–sub treatments of different cropping system: maize + chickpea sequential and maize/pigeon pea intercropping with four replications. The watershed was divided into four blocks (plot no. 1–8, 9–16, 17–24 and 26–32) with each block containing 8 plots.

Field operations

Two tillage methods (normal and minimum tillage) were compared under the Broad Bed and Furrow (BBF) landform. In normal tillage treatment, a sequence of operations such as chisel plough, mould board plough, ridge and blade harrow were carried out before the *kharif* season. In case of minimum tillage, only ridging operation was done for reshaping BBF. In case of no residues treatments, the entire crop residues are removed from the plot after harvesting, whereas in residues treatment all crop residues (100%) were spread on soil surface especially on the beds. In maize + chickpea cropping pattern, maize (cultivar: HTM 5401) was grown during *kharif* (monsoon) season and chickpea (cultivar: ICCV 2) grown in *rabi* (post-monsoon) season. In maize/pigeon pea, maize (cultivar: HTM 5401) and a long duration pigeon pea (cultivar: ICPH 2671) were sown together in *kharif* season. Fertilizer application during *kharif* season included basal application of di-ammonium phosphate (100 kg ha^{-1}), gypsum (200 kg ha^{-1}), Agribor as source of boron (2.5 kg ha^{-1}) and zinc sulphate (50 kg ha^{-1}). Two split doses (66% and 33%) of urea with total dose of 150 kg N ha^{-1} were applied by top dressing at 30 and 60 days after sowing. Micro-nutrients were applied once in two years. First application of micronutrients was done in 2010–11.

Monitoring of soil water and runoff

Calibrated neutron moisture meter was used to monitor soil water content (SWC) up to 1.2 m soil depth. First eight plots (shown in Figure 1 by rectangular boxes) were selected for monitoring SWC, which captured combinations of all different treatments. Three access tubes were installed in each treatment plot. Soil water was monitored at the fortnightly interval. Automatic runoff recorders were installed (after 2009) in five treatments plots (as shown by circles in Figure 1) namely, normal tillage with residue, normal tillage without residue, minimum tillage

Figure 1. Layout of the experiment. Numbers represent plots. Filled rectangular boxes represent plots with soil water monitoring setups, filled circles represent plots with runoff recorders and black dotted arrows represent direction of runoff flow.

Table 1. Depth-wise physical and chemical properties of soil at the experimental site

Depth (m)	Sand (%)	Silt (%)	Clay (%)	Water content (g g^{-1}) at 33 kPa	Water content (g g^{-1}) at 1500 kPa
0–0.15	27.3	22.9	49.9	0.34	0.26
0.15–0.3	25.4	20.9	53.7	0.37	0.28
0.3–0.6	23.7	20.5	55.8	0.40	0.30
0.6–0.9	21.3	20.4	58.3	0.43	0.32
0.9–1.2	21.2	20.0	58.8	0.43	0.32

Depth (m)	pH	EC (dS m^{-1})	Boron (ppm)	Sulphur (ppm)	Zinc (ppm)	Potassium (ppm)	Phosphorous (ppm)	Organic carbon (%)
0-0.15	7.9	0.22	0.44	8.48	0.62	172	4.74	0.42

without residues, minimum tillage with residues for maize + chickpea sequence system and minimum tillage with residues for maize/pigeon pea intercropping system.

Modelling field water balance

Generic soil water balance model was modified to represent CA practices on Vertisols. The field water balance equation is described by mass balance approach

$$\theta_t = \theta_{t-1} + R_t + I_t - E_t - T_t - DP_t - O_t, \tag{1}$$

where θ is the available water [L], t the time in days [T], R the rainfall [L], I the depth of irrigation [L], DP the deep percolation losses [L], O the runoff losses [L], E the evaporation [L], and T is the transpiration [L]. The weather data are collected from a local weather station at the ICRISAT.

Evapotranspiration

Values of evapotranspiration were estimated using dual coefficient method described by Allen *et al.*[22]. This method describes the estimation of crop coefficient (K_c) with respect to wetting pattern of the soil by splitting K_c into two separate coefficients, one for crop transpiration, i.e. the basal crop coefficient (K_{cb}) and one for soil evaporation (K_e).

$$ET_c = (K_{cb} + K_e)ET_0. \tag{2}$$

Values for K_{cb} were estimated following general guideline[23]. The K_{cb} values during initial, mid and at end of season were taken as 0.15, 1.1 and 0.3 for maize; 0.15, 0.9 and 0.3 for chickpea; and 0.15, 0.95 and 0.3 for pigeon pea respectively. In the case of intercropping, combined crop coefficient was estimated by taking weighted average of K_{cb} of both crops. In the present study, because of length of growing period of both crops is different, the maximum value between K_{cb} of both the crops was used for further calculations. The adjusted K_{cb} values give potential transpiration when the water available for plant uptake is not limited. The actual transpiration (T_a) can be estimated with respect to SWC depletion in root zone depth.

$$T_a = K_s \times K_{cb} \times ET_0, \tag{3}$$

$$K_s = \frac{\text{TAW} - D_r}{\text{TAW} - \text{RAW}}$$

$$\text{for } D_r > \text{RAW and } K_s = 1 \text{ for } D_r \le \text{RAW}, \tag{4}$$

$$\text{TAW} = 1000(\theta_{0.3} - \theta_{15})Z_r, \tag{5}$$

$$\text{RAW} = p\text{TAW}, \tag{6}$$

where K_s is the water stress coefficient, TAW the total available water in the root zone [L], RAW the readily available water in root zone [L], D_r the SWC depletion in the root zone [L], Z_r the root zone depth [L], $\theta_{0.3}$ and θ_{15} are SWC at 33 and 1500 kPa pressure [L L^{-1}], and p is the fraction of TAW that crop can extract from soil without suffering from water stress. A value of p was assumed to be 0.5.

Values of evaporation coefficient (K_e) are estimated using the formulae

$$K_e = K_r(K_{c\max} - K_{cb}) \le f_{ew}K_{c\max}, \tag{7}$$

where K_r is the dimensionless evaporation reduction coefficient dependent on the cumulative depth of water depleted from the top soil and f_{ew} is the fraction of the wetted soil that was not shaded from vegetation. Evaporation process in cracking soils was divided into three stages[22]. Stage 1, evaporation takes place from wet soil and continues until the soil water depletion is less than readily evaporable water (REW). For stage 1, evaporation value of K_r is equal to 1. In stage 2, value of K_r decreases as the soil water depletion exceeds REW. Value of K_r can be estimated as

$$K_r = K_{r2} + (1 - K_{r2}) \frac{\text{TEW}_2 - D_{e,i-1}}{\text{TEW}_2 - \text{REW}}, \quad \text{for } \text{TEW}_2 > D_{e,\,i-1} > \text{REW}, \tag{8}$$

where TEW_2 is the maximum cumulative depth of evaporation (depletion) from the soil surface layer when K_r is greater than K_{r2} (point at which evaporation transitions into stage 3 drying) [L], K_{r2} the value for K_r the junction of stage 2 and stage 3 drying, TEW the total evaporable water [L], D_e the SWC depletion due to evaporation and Z_e is the depth of the surface soil layer that is subject to evaporative flux [L]. Value of K_r at the transition point between stage 2 and stage 3 is in the range 0.1–0.4. In stage 3, K_r values further reduce to zero and can be calculated as

$$K_r = K_{r2} \frac{\text{TEW}_3 - D_{e,i-1}}{\text{TEW}_3 - \text{TEW}_2} \quad \text{for } \text{TEW}_3 > D_{e,i-1} > \text{TEW}_2, \tag{9}$$

where TEW_3 is the maximum cumulative depth of evaporation from the soil surface layer when K_r is equal to zero [L]. Allen *et al.*[22] used three-stage evaporation approach in cracking heavy clay soil. Values used in their study were REW = 8 mm, TEW_2 = 50 mm, TEW_3 = 100 mm, and K_{r2} = 0.2. In the current study, values of these parameters were changed to get better fit between observed and simulated SWC and runoff. Further, it was assumed that addition of crop residue reduces evaporation by 20%, but not during rainfall.

Runoff

The empirical runoff equation was used to estimate surface runoff.

$$R = \frac{(P - 0.2 \times S)^2}{(P + 0.8 \times S)}, \tag{10}$$

$$S = \frac{(25{,}400 - 254 \times \text{CN})}{\text{CN}}, \tag{11}$$

where CN is the curve number of a day under average soil water condition (CN_2). Value of CN_2 depends on land use cover, soil hydrological characteristics, topography and cropping system. Further adjustment in the selected curve number may be done with respect to antecedent water condition. Neitsch *et al.*[24] have presented expressions to compute curve number for dry (CN_1) and wet (CN_3) situations. In the present computation procedure, the curve number was adjusted with respect to daily water content in terms of relative saturation. The equation for adjusting curve number to dry situation was adapted from Neitsch *et al.*[24], whereas for wet situation, instead of a constant, a parameter β as a function of S_e was included in the expression as suggested by Neitsch *et al.*[24]. The following are the expressions used for estimating daily curve number.

$$\text{CN}_1 = \text{CN}_2 - \frac{20(100 - \text{CN}_2)}{(100 - \text{CN}_2 + \exp[2.533 - 0.0636(100 - \text{CN}_2)])}, \tag{12}$$

$$\text{CN}_3 = \text{CN}_2 \ \exp[\beta(100 - \text{CN}_2)], \tag{13}$$

$$\beta = 10^{(2.098Se^2 - 1.818Se - 2.257)}, \tag{14}$$

$$S_e = \frac{\sum_{j=1}^{100} \frac{\theta_{i,j} - \theta_{15_j}}{\theta_{s_j} - \theta_{15_j}}}{100}. \tag{15}$$

where S_e is relative saturation with respect to water content at saturated and permanent wilting point. The purpose of using SWC-based expression for estimating curve number is that the Vertisols swell after wetting which significantly reduces infiltration rate to generate more runoff. On the other hand, when the soils are dry, the cracks in the soil allow rapid infiltration and reduce the runoff.

Soil water dynamics

A simple and one-dimensional mass balance approach was implemented to simulate soil water dynamics. The model assumes that the given soil profile is a stack of thin soil layers. Upper compartment first gets filled with water whenever there is rainfall or irrigation; and subsequently the lower one fills or partially fills depending on spillover amount. Upper maximum limit for refilling soil is saturated water content (θ_S) and lower limit for water depletion is $0.5\theta_{15}$ in case of evaporation. While during crop water uptake, roots may use water which is available within root zone (greater than θ_{15}). Upward movement of water within soil profile has not been considered in the current modelling. Curve numbers were optimized to get better fit between observed and simulated runoff and water content using the observed data of three years. The model was further used for long-term simulation (between 1974 and 2010) under the maize–chickpea cropping system using ICRISAT weather data.

Developing production function

FAO described the linear relationships between crop yield and water use, where relative yield reduction (ratio of actual grain yield and maximum achievable yield) is related to the corresponding relative reduction in evapotranspiration (ratio of total evapotranspiration in a given condition and non-limiting water availability)[25]. In the present study, a linear relationship between relative reduction in evapotranspiration (E_R) and the total grain yield was used to develop linear production functions. Production function was developed for maize + chickpea cropping system from long-term strategic research data (grain yield data from 1974 to 2010) of ICRISAT research station.

Simulating impact of CA on crop yield

To parameterize the effects of long-term adaptation of CA practices, it was assumed that water holding capacity of soil will be increased by 20% (ref. 26), therefore available water capacity of surface 0.6 m soil layer was increased accordingly, but all other parameters are kept similar to base line (minimum tillage with residue application). Simulations for 36 years (1974–2010) period were carried out to capture wide range of climatic variability. Crop yields were simulated using derived crop production function. On an average, total rainfall received during maize cropping period was 684 mm (standard deviation = 200 mm and median 597 mm), whereas during chickpea growing period average rainfall was only 22 mm (standard deviation = 32 mm and median 13 mm). Impact of CA practices was assessed for four rainfall classes: <25‰, 25‰ to median, median to 75‰ and >75‰. For maize growing period four rainfall classes were <498 mm, 498–597 mm, 597–903 mm and >903 mm. In case of chickpea, rainfall classes were <532 mm, 532–650 mm, 650–916 mm and >916 mm.

Water productivity

Water productivity (WP) was estimated with respect to total water input that included rainfall received during the growing period and stored soil water. Maize grain equivalent yield (kg ha^{-1}) of both crops in cropping system was used for estimating the WP values. Equivalent grain yield was estimated assuming minimum support prices for maize of Rs 840 per quintal; chickpea, Rs 1760 per quintal and pigeon pea, Rs 2300 per quintal for the year 2009–10. The same prices were used for other two years.

Results and discussion

Observed runoff and soil water data were used to modify soil water balance model to describe effects of CA practices on Vertisols. Modified model was used to develop relationship between observed grain yield and estimated reduction in evapotranspiration. Finally, long-term impact of CA practices on crop yield and runoff was assessed using the modified soil water balance model and relationship between grain yield and reduction in evapotranspiration.

Soil water balance

Total rainfall received during maize growing period (June–October) was 780 and 933 mm in 2009–10 and 2010–11 respectively. Cumulative rainfall and runoff during maize growing period are shown in Figure 2. Observed runoff data during June–August 2010 indicated that out of 565 mm rainfall, 46.3% and 44.8% left the fields as runoff from treatments without residues retention compared to 35.7% and 33.1% from treatments with residues retention for normal and minimum tillage respectively, in maize + chickpea system. Similarly, runoff from minimum tillage with residue retention in maize/pigeon pea system was 37.8% of the rainfall. High rainfall events during July and August were resulted in sharp increase in cumulative runoff. Figure 2 indicates that crop residue on surface reduced the runoff generation as observed earlier[1,2,27,28]. Runoff from both conventional tillage and minimum tillage was similar. Similarity between runoff for minimum tillage and conventional tillage might be because of the wet Vertisols reducing the infiltration rate and BBF system in both tillage treatments to allow excess water to flow easily[27,29].

Data on soil water monitored at 0–1.2 m soil depth are presented for maize + chickpea and maize/pigeon pea plots for 2010–11 (Figure 3). Average amount of soil water stored over the *kharif* and *rabi* seasons is shown for different treatment plots. In general, the soil water availability during *kharif* season was almost similar among the different treatment plots. Frequent rainfall during monsoon compensated the difference occurred due to tillage treatment and residue application on overall soil water. However, soil moisture content in the minimum tillage plots with residue application was maximum among the

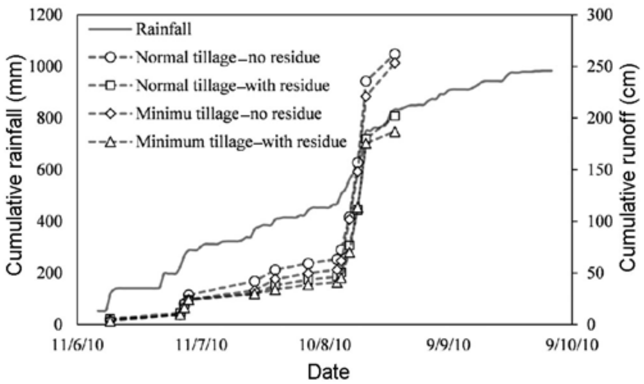

Figure 2. Cumulative rainfall and runoff recorded during *kharif* season, 2010.

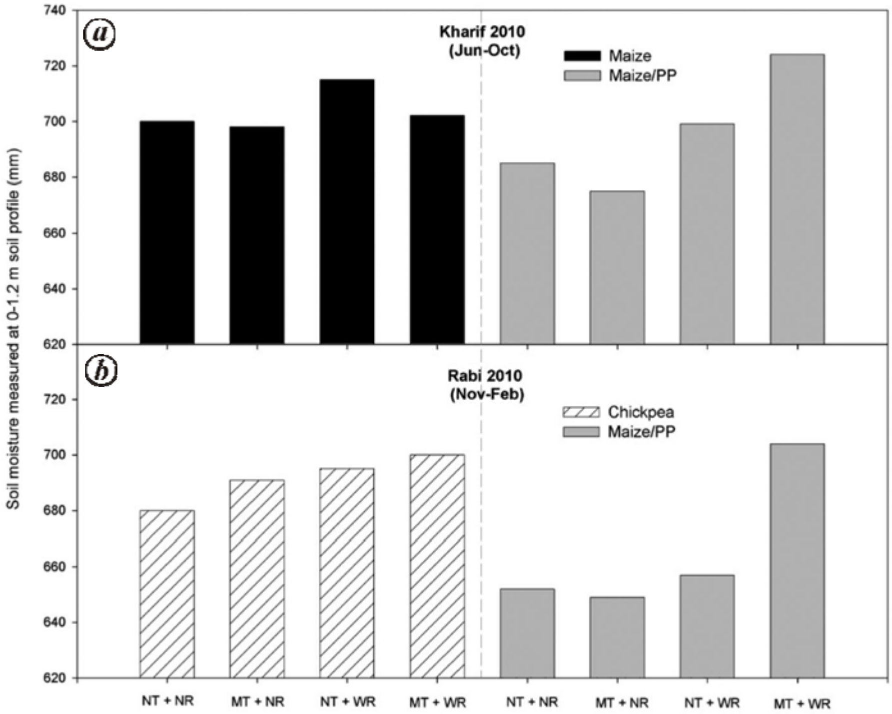

Figure 3. Average soil water measured at 0–1.2 m soil profile for (***a***) maize and maize/pigeon pea plots during *kharif* season 2010; (***b***) chickpea and maize/pigeon pea plots during *rabi* season 2010. NT, Normal tillage; MT, Minimum tillage; NR, No residue; WR, With residue.

Table 2. Average crop yield (maize, chickpea and pigeon pea) obtained from maize–chickpea and maize/pigeon pea cropping system under various treatments

		Maize (mg ha^{-1})			Chickpea (mg ha^{-1})			Maize (mg ha^{-1})			Pigeon pea (mg ha^{-1})		
Tillage	Residue	2009	2010	2011	2009	2010	2011	2009	2010	2011	2009	2010	2011
Conventional	No	4.02	6.45	5.54	0.47	1.15	0.00	3.72	6.01	6.14	0.91	0.36	0.51
	Yes	4.08	5.75	5.11	0.40	1.12	0.00	3.24	5.55	5.61	0.97	0.40	0.41
Minimum	No	3.93	6.53	5.07	0.42	0.75	0.00	3.58	4.75	5.38	0.95	0.51	0.53
	Yes	3.98	6.02	4.79	0.40	0.83	0.00	3.52	6.09	5.23	0.84	0.44	0.51

treatments (Figure 3). Application of crop residues was more effective than tillage treatment. Soil water availability in *rabi* season differed with treatment. Minimum tillage with residue application resulted in more green water than other treatment plots (Figure 3).

In case of maize + chickpea sequential cropping, soil water in conventional tillage plots was higher than the minimum tillage plots during *kharif* season. Poor distribution of rainfall and the high consumptive water usage by maize crop during late growing period led to formation of a network of deep cracks[30]. These cracks play important role in soil water dynamics in Vertisols[31,32]. Water in dry Vertisols moves through preferential flow to deeper layers and significantly reduces surface runoff. In contrast to the infiltration process, open cracks may enhance evaporative flux as direct evaporation might be possible through deep soil layers[20,32]. Conventional tillage practice disintegrates larger soil clods into finer pieces and fills wider-cracks with loose soil, which may result into early closing of cracks. This may impair the preferential flow and increase the runoff, though it may also reduce the direct evaporation from deeper soil layers. Presence of cracks in untilled soil allows more rainwater to seep into deeper soil layers. In addition to cracks, crop residue provides obstruction to runoff and evaporation and thus conserves water[2].

Crop yield and water productivity

Total grain yield for all three crops (maize, chickpea and pigeon pea) in different treatments is shown in Table 2. Irrespective of treatment, average maize yield in maize+ chickpea system was 4.0, 6.2 and 5.1 mg ha^{-1} in 2009,

Table 3. Parameters optimized for capturing tillage and residue effect in Vertisols during model calibration

	Normal tillage		Minimum tillage	
	No residue	With residue	No residue	With residue
Curve number	77	69	76	68
Soil depth (m)	1.2	1.2	1.2	1.2
Z_e (m)	0.15	0.15	0.30	0.30
REW (m)	0.008	0.008	0.016	0.016
TEW_2 (m)	0.05	0.05	0.05	0.05
TEW_3 (m)	0.22	0.22	0.22	0.22
Kr_2	0.2	0.2	0.2	0.2

Z_e is depth of soil subjected to evaporation, REW is the depth of readily evaporable water, TEW_2 is the maximum cumulative depth of evaporation (depletion) from the soil surface layer when evaporation reduction coefficient (K_r) is greater than K_{r2}, TEW_3 is the maximum cumulative depth of evaporation from the soil surface layer when K_r is equal to zero, and K_{r2} is the K_r at which evaporation transitions into stage three drying.

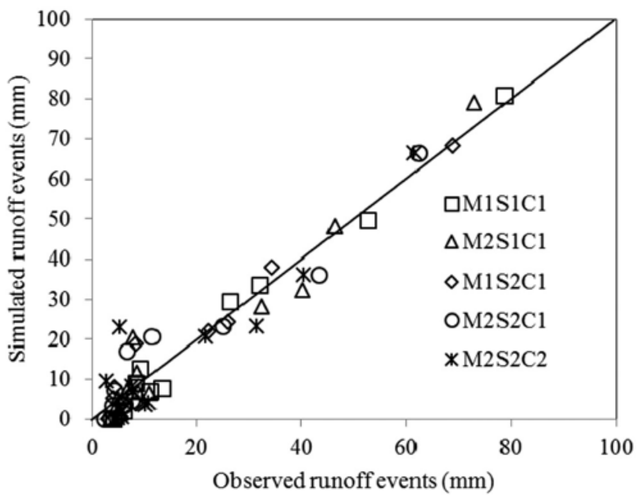

Figure 4. Observed and simulated runoff volumes for the event occurred during 2010 (maize–chickpea cropping system).

2010 and 2011 respectively. On the other hand, average maize yield in maize/pigeon pea system was 3.5, 5.1 and 5.6 mg ha^{-1} in respective three years. Maize yield in 2010–11 and 2011–12 was 30–40% higher than that in 2009–10. There are two important reasons for poor maize yield in 2009–10: (i) poor rainfall distribution and water logging and (ii) deficiency of micro-nutrients. Poor rainfall distribution during 2009–10 had led to a water logging situation at the beginning of the crop growth stage. Moreover results of soil analysis showed that the soil at experimental site was deficient in zinc, sulphur and boron, which is important yield-limiting factor[33]. Micronutrients (zinc, boron and sulphur application) along with major nutrients were also applied in the year 2010–11.

Comparison of maize yield between maize + chickpea sequential system and maize/pigeon pea intercropping showed that maize yield in the case of maize + chickpea sequential system was 10% higher than the maize/pigeon pea intercropping system during 2009–10 and 2010–11. Interestingly, maize yield obtained from maize/pigeon pea intercropping was higher than the sole maize (maize + chickpea system) in the year 2011. Increase in maize yield with pigeon pea intercropping is attributed to replenishment of N in soil through biological N fixation and N release from incorporated residue of pigeon pea[7]. Irrespective of the treatment, chickpea yield during *rabi* season in maize + chickpea system was on an average 0.42 and 0.96 mg ha^{-1} in 2009–10 and 2010–11 respectively. Despite normal rainfall during 2009–10, chickpea in *rabi* experienced water scarcity which resulted in relatively lesser yield (nearly half) than 2010–11. Whereas total rainfall received during 2011–12 was only 525 mm which resulted in entire crop failure of chickpea. On the other hand, early established deep rooting system in pigeon pea used *in situ* soil water from deep soil layers during post-rainy season. Thus although chickpea crop entirely failed during 2011–12, pigeon pea yield was nearly 0.49 mg ha^{-1}. Pigeon pea yield was also linked to rainfall distribution. Higher yields were observed during 2009 when the rainfall was near to normal as compared to low yield when the rainfall was 40% deficit in 2011. Poor yield in 2010 was due to insect attack on pigeon pea.

Crop yield obtained from different treatments (tillage and residue) was not significant. One of the reasons could be that soils at experimental site were deep and crop water requirements at most of the time were fulfilled both in conventional and conservation systems except in 2011–12, as the rainfall received at experimental site was normal and above normal.

Water productivity values for maize + chickpea cropping system were 0.48, 0.70 and 0.98 kg m^{-3} as compared to 0.55, 0.64 and 1.4 kg m^{-3} for maize/pigeon pea system during 2009, 2010 and 2011 respectively. Higher water productivity for maize/pigeon pea system in 2009 was because of high value of pigeon pea compared to chickpea, whereas less water productivity in 2010 was because

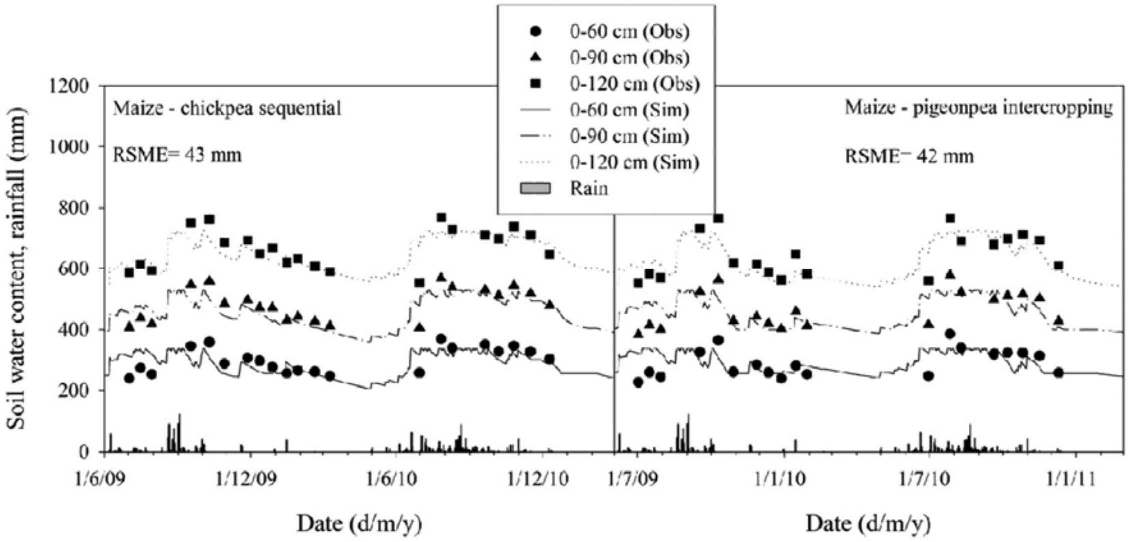

Figure 5. Observed and simulated water content in soil profile for conventional tillage and without residue and maize–chickpea cropping pattern and maize–pigeon pea intercropping.

of low pigeon pea yields. In 2011, despite the low rainfall, high water productivity values indicated the grain produced per unit rainfall was greater than previous two years. The success of maize/pigeon pea intercropping system also indicated possible adaptation strategy for climate smart agriculture[4].

Calibration of soil water balance model

Table 3 shows the parameters optimized for capturing tillage and residue effect on field scale hydrology. Figure 4 shows simulated and observed runoff event during maize growth period in 2010. Observed surface runoff is well captured with simulated values for different tillage and residue treatments. Modified curve numbers for no residues and with residues retention treatment were 77 and 69 respectively, for normal tillage. In case of minimum tillage, curve number reduced by one compared to normal tillage. Root mean square error (RMSE) and coefficient of determination (R^2) between observed and simulated runoff was 5.2 mm and 0.94 respectively. Similarly, Figure 5 shows observed and simulated soil water from June 2009 to March 2011 for selected treatment (conventional tillage and without crop residue) under maize + chickpea and maize/pigeon pea cropping system. The modified soil and water balance model captured soil water dynamic reasonably well. Depth of soil available for evaporation for normal tillage was assumed to be 0.15 m compared to 0.30 m for minimum tillage soil. The basis of this assumption is that soil with minimum tillage treatment showed cracks on the soil surface. RMSE in estimating soil water was 43 mm and 42 mm under maize + chickpea and maize/pigeon pea cropping system respectively.

Relationship between relative evapotranspiration reduction and grain yield

Calibrated soil water balance model used to simulate maize + chickpea cropping system for twelve years between 1974 and 2010. Production functions for maize and chickpea yield were developed using simulated relative reduction in evapotranspiration and observed grain yields. Relative reduction in evapotranspiration during *kharif* season varies between 0% and 19%, whereas during the chickpea growing season it is between 27% and 78%. Figure 6 shows the relationship obtained for production functions of maize and chickpea. Data points ($n = 12$) in these figures represent grain yield of maize (Figure 6 *a*) and chickpea (Figure 6 *b*). The conditions assumed in these simulations are representative to normal tillage without residue retention. Linear equation obtained for maize and chickpea yield as a function of relative reduction in evapotranspiration was used to assess impact of conservation agricultural practices on grain yield.

Long-term impact of CA on surface runoff and crop yield

Figure 7 shows the effects of conventional and CA on simulated runoff in different rainfall years. Results showed that CA had large impact on reducing surface runoff compared to conventional practice. Runoff reduction in dry years was higher compared to wet years. On an average, conservation practice reduced surface runoff by 30% compared to the conventional practices. This amount enhances soil water availability for plant uptake and also contributes in deep percolation. Figure 8 shows simulated average maize (Figure 8 *a*) and chickpea (Figure 8 *b*)

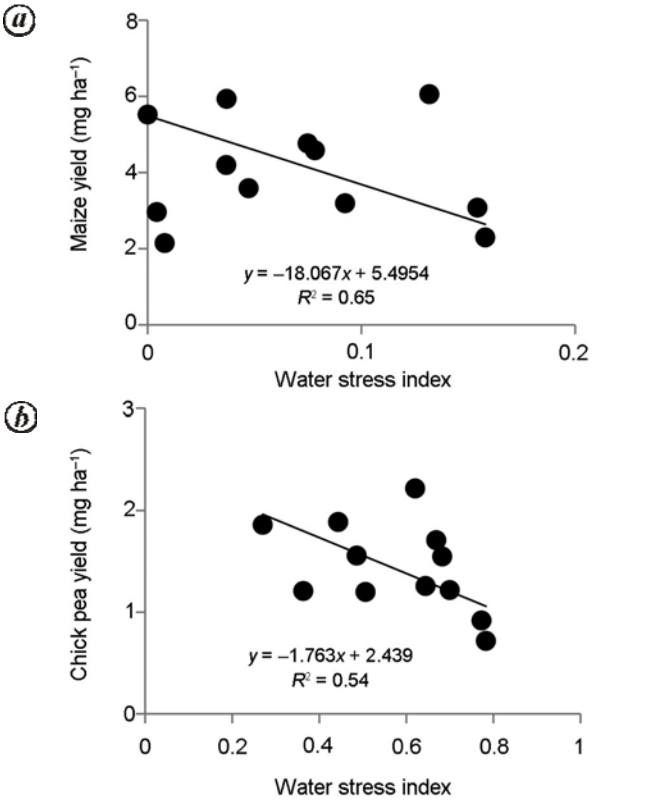

Figure 6. Relationship between observed grain yield and simulated water stress index for (***a***) maize; (***b***) chickpea.

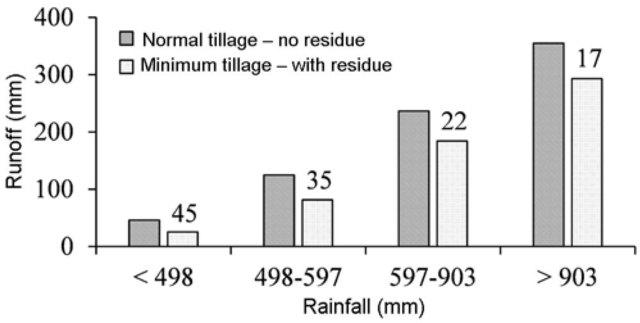

Figure 7. Effects of tillage and residue treatments on simulated runoff during maize growing period for 36 years (1974–2011). Four rainfall classes represent the quantity less than first quartile, between first and second quartile, between second and third quartile, greater than third quartile.

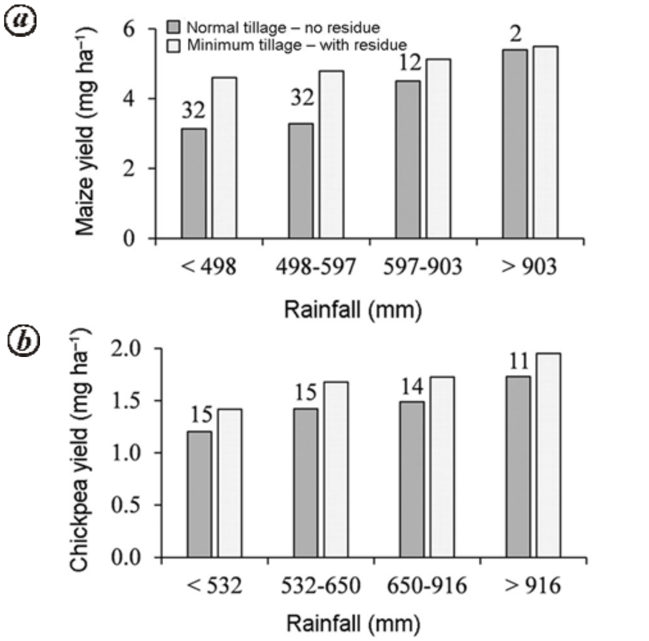

Figure 8. Effects of tillage and residue treatments on estimated yield of maize (***a***) and chickpea (***b***) for 36 years (1974–2011). Four rainfall classes represent the quantity less than first quartile, between first and second quartile, between second and third quartile, greater than third quartile.

yield relative to rainfall classes. Simulation results showed that CA enhanced maize yield by 46% in low rainfall years compared to conventional system. Yield increase during high rainfall years ranged between 2% and 15%. In case of chickpea, additional *in situ* soil water resulted into 13–18% more crop yield compared to the conventional practice.

Simulations showed that conservation practice has potential to build system resilience for alleviating water scarcity in rained areas and reduce risk of crop failure. There was no significant difference in crop yields between conventional and conservation system during normal and wet years, but it helped in enhancing ecosystem services such as deep percolation and groundwater recharge. Moreover, reduced surface runoff helped in reducing water logging and flooding situation at downstream location and reducing soil erosion.

Conclusions

Effects of conservation agriculture practices on crop yield and field scale hydrology were analysed and modelled using three-year field experimental data. Water productivity values were estimated based on maize equivalent grain yield, total rainfall received and simulated soil water content. Maize/pigeon pea intercropping system is more sustainable and associated with less risk compared to maize + chickpea sequential cropping system. In terms of soil and water conservation, surface runoff observed in conservation practices was 28% less compared to the conventional system, which may be attributed to residues retention than minimum tillage. The long-term simulation results showed that CA helps in reducing water stress in dry years and reduces the risk of crop failure.

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