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Modelling soil water balance and root water uptake in cotton grown under different soil conservation practices in the Indo-Gangetic Plain



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ABSTRACT

Although soil conservation practices are being promoted as better environmental protection technologies than traditional farmers' practice, limited information is available on how these practices affect soil water balance and root water uptake. The root water uptake (*RWU*) patterns of cotton grown under soil conservation practices and soil water balance in cotton (*Gossypium hirsutum* L.) fields under a cotton-wheat (*Triticum aestivum* L.) cropping system were analyzed using the Hydrus-2D model. The treatments were: conventional tillage (CT), zero tillage (ZT), permanent narrow beds (PNB), permanent broad beds (PBB), ZT with residue (ZT+R), PNB with residue (PNB+R) and PBB with residue (PBB+R). Results in the third year of the cotton crop indicated that the surface (0–15 cm layer) field saturated hydraulic conductivity in both PNB and PBB plots were similar and were significantly higher than in the ZT plots. Computed potential transpiration rates (T_{rp}) under CT were lower than in other treatments, due to less radiation interception and lower Leaf Area Index (*LAI*). Both PNB and PBB plots had higher T_{rp} and crop yields than CT plots, which were further improved by residue retention. Predicted soil water content (*SWC*) patterns during the simulation periods of third and fourth years showed strong correlation ($R^2 = 0.88$, $n = 105$, $P < 0.001$, the root mean square error (*RMSE*) = 0.025, and the average relative error (*AVE*) = 7.5% for the third year and $R^2 = 0.81$, $n = 105$, $P < 0.001$, *RMSE* = 0.021, and *AVE* = 9% for the fourth year) with the actual field measured *SWCs*. Cumulative *RWU* (mm) were in the order: ZT (143) < CT (157) < PNB (163) < ZT+R (174) < PBB (188) < PNB+R (198) < PBB+R (226). Thus, PBB+R and PNB+R practices could be adopted for cotton cultivation, as these enhanced root growth and improved radiation interception and *LAI*. The Hydrus-2D model may be adopted for managing efficient water use, as it can simulate the temporal changes in *SWC* and actual transpiration rates of a crop/cropping system.

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1. Introduction

In the conventional systems involving intensive tillage, there is a gradual decline in soil organic matter (SOM) through accelerated oxidation and burning of crop residues (which is a common

practice in the upper Indo-Gangetic Plains). This causes environmental pollution and loss of valuable plant nutrients. Hence, resource conservation issues have drawn the attention of scientists to devise innovative soil conservation practices for higher productivity (Bhattacharya et al., 2015). Conservation agriculture (CA), one such novel soil conservation practice, involves minimum soil disturbance, providing a soil cover through crop residues or other cover crops, and crop rotations for achieving higher productivity and minimizing adverse environmental impacts (Hobbs et al., 2007; FAO, 2010). When the crop residues are retained on the soil surface, it initiates processes that lead to improved soil quality by protecting the soil from raindrops and limiting water evaporation. Therefore, CA may lead to sustainable improvements in the efficient use of water by increasing infiltration and soil water retention and reducing water losses

Abbreviations: CT, conventional tillage; ZT, zero tillage; PNB, permanent narrow beds; PBB, permanent broad beds; ZT+R, ZT with residue; PNB+R, PNB with residue; PBB+R, PBB with residue; *RWU*, root water uptake; *RLD*, root length density; *SWC*, soil water content; *BD*, bulk density; *DAS*, days after sowing; T_{rp} , potential transpiration; T_{ra} , actual transpiration; *RMSE*, root mean square error; *AVE*, average relative error; *SOM*, soil organic matter; *IGP*, Indo-Gangetic Plains.

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due to evaporation, and by improving nutrient balances and their availability (Dahiya et al., 2007; Govaerts et al., 2007; Verhulst et al., 2010; Bhattacharya et al., 2013). CA also improves soil health (mainly by increasing SOM content).

Studies on zero tillage (ZT) and bed planting technologies have largely been conducted on wheat in the rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) cropping system in the Indo-Gangetic Plains (IGP). There is already greater emphasis on crop diversification, due to growing concerns about the unsustainability of the rice–wheat system in this region (Bhandari et al., 2003; Aggarwal et al., 2004). In this context, a crop such as cotton (*Gossypium hirsutum* L.) has emerged as a promising alternative to rice in the Kharif (rainy) season (Das et al., 2014). In this region, especially in the states of Uttar Pradesh, Punjab, Haryana and Rajasthan, >95% of the area of rice and wheat area under irrigation. All these conditions call for efficient use of resources to achieve sustainable production that can minimize water use. Potential improved productivity and assured high returns could be realized from the cotton–wheat system, thereby improving the livelihood of farmers in the region (Mayee et al., 2008).

The raised bed technology enhances water use efficiency, improves soil physical environment and encourages root proliferation that gives better yields for upland crops, including maize (*Zea mays* L.), wheat, soybean (*Glycine max* L.) and cotton (Sayre and Hobbs, 2004; Zhongming and Fahong, 2005; Aggarwal et al., 2006; Thierfelder and Wall, 2012; Ahmad et al., 2014). Ahmad et al. (2011) indicated that the bed-furrow system (60 cm bed and 30 cm furrow) is most suited for cotton when the plant-to-plant distance was maintained at 30 cm. Selected geometries of bed-furrow planting of cotton were further evaluated for water savings compared with traditional practices of flat sowing. Results obtained from cotton fields showed a 40% water saving and ~10–15% yield increase in the IGP. The results thus suggested that the raised bed technology has sufficient potential to economize water use and improve water productivity of cotton-based cropping systems (Tursunov, 2008).

For both ZT and bed planting methods, retention of residues on the surface can modify soil water content. If the soil surface is covered with residues, it is shielded from solar radiation and hence the evaporation rate from the surface is less than bare soils. In addition, an increase in the thickness of the boundary layer between soil and (open) atmosphere also decreases evaporation rates. Although the surface moisture under the residue will evaporate slower, after the wetting event, cumulative evaporation from the residue-covered surface can exceed that of the bare surface (Van Donk et al., 2010).

Numerical simulations are an efficient approach to investigate soil water dynamics for optimal irrigation management practices (Meshkat et al., 1999; Cote et al., 2003). Many studies have showed that numerically simulated soil water data agree with field data. For instance, De Silva et al. (2008) used Hydrus (2D/3D) to numerically evaluate root water uptake (RWU) and soil water movement in land areas with a mixture of natural vegetative cover (i.e. trees and grasses) and concluded that different irrigation amounts and frequencies should be used for different plant species in irrigated strip intercropping fields. Deb et al. (2013) evaluated spatio-temporal compensated and uncompensated RWU patterns of mature pecan trees in a silty clay loam orchard using the Hydrus (2D/3D) model. They concluded that: (i) simulated soil water contents (SWCs) and temperatures at different times agreed well with measured soil water contents and temperatures and that (ii) simulated transpiration and relative transpiration values were strongly correlated with measured transpiration and plant-based water stress indicators (stem and leaf water potentials) (Deb et al., 2013). In another field study, Buttar et al. (2006) revealed that wheat productivity per unit irrigation water was higher in the plots

under the bed planting method compared with the conventionally planted plots. Irrigation scheduling based on the CERES ('Crop Environment Resource Synthesis') Model (Ritchie, 1998) performed better than a conventional farmers' practice (Arora et al., 2007).

Skaggs et al. (2004) compared Hydrus-2D simulations of water infiltration and redistribution with field data (at the San Joaquin Valley Agricultural Sciences Center, located near Fresno, California) and observed that the Hydrus-2D predictions of the water content distributions were in very good agreement with field data. Their results supported the use of the Hydrus-2D Model as a tool for investigating and designing drip irrigation management practices. In a study of Bufon et al. (2012), the latest version of the Hydrus-2D Model was used to simulate soil water movement under different irrigation rates and environmental conditions during cotton growth on beds. The results indicated that SWC data simulated by Hydrus-2D were very accurate (deviations were $\leq \pm 3\%$). These studies confirmed that the Hydrus-2D Model can be used to evaluate irrigation strategies for cotton.

The major goals of this study were: (i) to calibrate and validate the Hydrus-2D Model for predicting soil water distributions under conventional and soil conservation practices (ZT, and broad and narrow beds with residue retention) of growing cotton in the IGP and (ii) to simulate changes in SWC in the cotton root zone and RWU during drying of an initially watered soil under soil conservation practices. It was hypothesized that: (i) permanent beds would promote root growth, RWU and leaf area, due to less soil compaction (Mishra et al., 2015) and more solar radiation interception, and that (ii) retention of previous crop residues would further improve SWC and RWU due to less evaporation loss. The specific objectives of the study were: (i) to analyse the impacts of permanent narrow and broad beds versus conventional tillage (CT) on SWC distributions and RWU patterns for cotton using the Hydrus-2D Model and (ii) to evaluate the effects of residue retention in PNB and PBB plots on RWU by cotton.

2. Materials and methods

2.1. Field experiment

A CA experiment was initiated in May 2010 at the research farm of the Indian Agricultural Research Institute (IARI), New Delhi, India, on an alluvial sandy clay loam soil (fine loamy, illitic, Typic Haplustept) with cotton and wheat as successive crops in a year. This area is characterized by a semi-arid climate, with high summer ambient temperatures, high wind speed and an erratic rainfall distribution. The weather data at the experimental site during the crop growth of the third and fourth years are presented in Fig. S1 (Supplementary Information). In both years, maximum and minimum temperatures during crop seasons varied between 24.2–46.5 °C and 5.5–32.2 °C, respectively. During the entire crop seasons in 2012 and 2013, total rainfall was 494 and 1350 mm, respectively. Pan evaporation varied between 1.5–13.8 mm d⁻¹ in both years.

The surface (0–15 cm) soil of the experimental site had pH 7.7, Walkley-Black organic C 5.2 g kg⁻¹, KMnO₄ oxidizable N 182.3 kg ha⁻¹, 0.5 M NaHCO₃ extractable P 23.3 kg ha⁻¹, and 1 N NH₄OAc extractable K 250.5 kg ha⁻¹. The proportions of sand, silt and clay in the 0–15 cm soil layer were 49.6, 23.2, and 27.2, respectively. The corresponding values for the 15–30 cm layer were 40.4, 24.5 and 35.1, and for the 30–45 cm layer were 42.1, 26.5 and 31.4, respectively. Thus soil texture of the 0–15, 15–30 and 30–45 cm layers were sandy clay loam, clay loam and clay loam, respectively.

The experimental treatments consisted of conventional tillage (CT), permanent narrow bed (one row of cotton per 40 cm wide bed and 30 cm wide furrow) (PNB), permanent broad bed (two rows of

cotton per 100 cm wide bed and 40 cm wide furrow) (PBB), PBB with residue (PBB+R), and PNB with residue (PNB+R). These treatments were established in 2010. From 2011 onwards, two additional treatments involving zero tillage (ZT) either with (ZT+R) or without residue retention of previous crops were established. Thus, the study involved six soil conservation practices. Among these, three (ZT+R, PBB+R and PNB+R) could be considered CA practices. The experiment was laid-out in a randomized block design (size: 10.0 m × 8.4 m) with three replications for each treatment. The planting design and root sampling scheme for both years under different treatments are reported in Fig. 1. After harvest, both cotton and wheat residues were taken away from the residue removal plots. However, tender cotton twigs and leaves (~20% of the total cotton residues) and ~40% of the wheat residues were retained at the soil surface in all residue retained plots. In both CT and ZT plots with residue removal, very little cotton stalk and wheat stubble (~10–15 cm) remained anchored after crop harvests. Conventional tillage involved one deep (~30 cm) ploughing with a disc plough followed by two ploughings each with a disc harrow and cultivator, while no ploughing was done in the ZT treatment in any year. Fresh raised-beds were prepared under PBB and PNB in 2010 with a bed planter, while the beds were reshaped once a year before sowing of cotton using a bed planter. Other details of the experiment are presented by Das et al. (2014) and Mishra et al. (2015).

In all years, Bt cotton (cultivar MRC-7017) was sown manually by the end of May at 70 × 60 cm spacing and harvested in the second fortnight of November. A common dose of 150 kg N + 60 kg P₂O₅ + 40 kg K₂O ha⁻¹ was applied to cotton, of which, P and K were applied as basal along with 50% of the N. The remaining N was applied in two equal splits at 30 and 60 days after sowing (DAS) of cotton. Herbicide glyphosate was applied at 1.0 kg ha⁻¹ in the ZT

plots about one week before sowing of both crops. Pendimethalin was applied at 0.75 kg ha⁻¹ as pre-emergence at 2–3 DAS.

In addition to one pre-sowing irrigation, eight irrigations were given to all treatments. In the CT and ZT plots, irrigation was applied using a flooding method and the total applied water was more than PNB and PBB plots, where irrigation water was applied in furrows. The irrigation water depth applied to each experimental plot was usually measured four times during each irrigation period using a digital velocity meter and the wetted area of the field channel. The details of the measurement procedure are given in Das et al. (2014). In 2012, total irrigation water applied (including a pre-sowing irrigation) during the entire cotton crop in the plots under CT, PNB, PNB + R, PBB, PBB + R, ZT + R and ZT in 2012 (third year) were 621, 549, 540, 527, 504, 558 and 603 mm, respectively. In 2013, the corresponding values were 1350, 1255, 1248, 1235, 1220, 1290 and 1265 mm, respectively.

2.2. Selection of simulation period

Model simulations of RWU patterns of cotton and SWC distributions in the soil profile were performed during 25–122 days after sowing (DAS) in both years. The initial 0–25 DAS period was omitted, because root growth, presented in terms of root length density (RLD) and average root system diameter (important input variables of the model), was very small to make any significant contribution to total RWU of the season.

2.3. Measurement of soil hydraulic properties

In 2012, undisturbed core samples (with a core of 5.0 cm diameter and 117.5 cm³ volume) were collected from all plots (in triplicate from each plot) from the 0–15, 15–30 and 30–45 cm soil

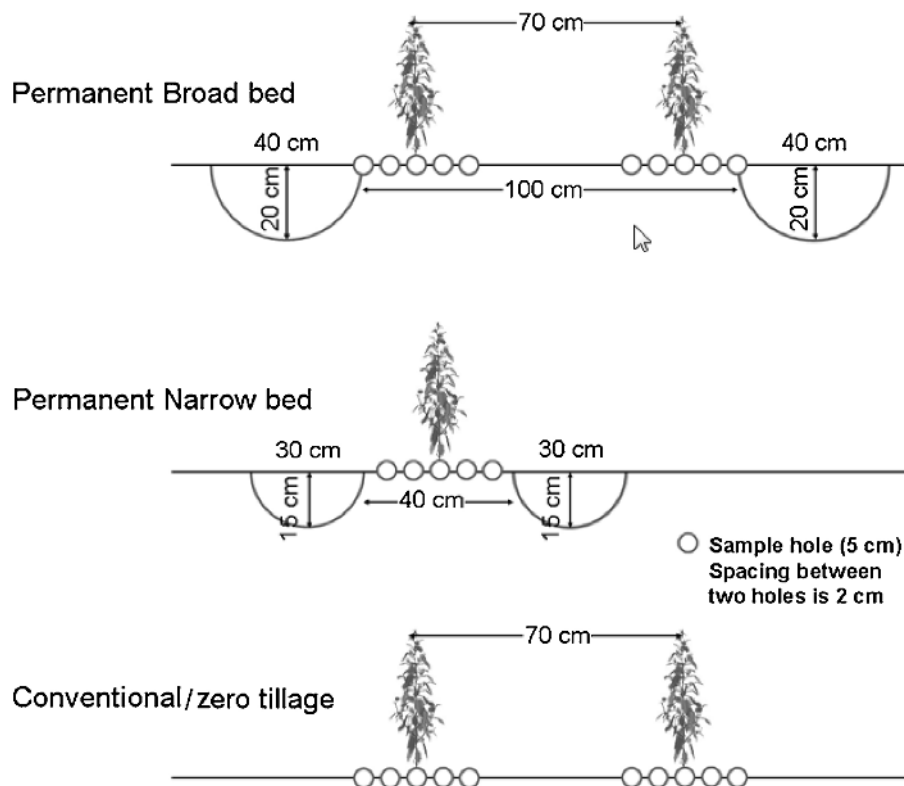


Fig. 1. Planting design and root sampling scheme for different soil conservation practices: Permanent broad bed (PBB), Permanent narrow bed (PNB), Conventional tillage (CT), and Zero tillage (ZT).

depths at 30, 60 and 90 DAS of the cotton crop for soil bulk density (BD) determination. Soil cores were used for the determination of SWCs at 0, 0.33, 1, 2, 5, 10 and 15 bar using a pressure plate apparatus (Klute, 1986). Soil water contents in the soil profile (0–45 cm layer) at 15 cm intervals were also measured gravimetrically on 30, 40, 45, 80, 100 and 105 DAS in years 2012 and 2013. Soil texture was measured following the international pipette method (Gee and Bauder, 1986). Field-saturated hydraulic conductivity (K_s) was determined at 0–15, 15–30 and 30–45 cm soil layers using a Guelph Permeameter (Reynolds and Elrick, 1991; Reynolds et al., 2002).

2.4. Root sampling, scanning and analysis

At 30, 60 and 90 DAS, destructive samplings for *RLD* measurement in all plots were performed. A 5 cm diameter sampler was used to collect root samples ($\sim 200 \text{ cm}^3$) from the

0–15, 15–30, and 30–45 cm soil layers from all plots to study the vertical and horizontal distribution of roots around plants. Root samples were taken at different growth stages of the cotton crop (in the middle of the simulation period). Sampling depths were restricted to 45 cm since *RLD* was negligible ($< 0.05 \text{ cm cm}^{-3}$) below 45 cm depth. Root samples were taken from the centre of a row by placing the core auger, such that the centre of the core coincided with the base of the cut plant (Aggarwal et al., 2006). Another four root samples were taken at 2 cm intervals from the left and right of the central soil core (Fig. 1). After excavation, soil cores were sealed in polythene bags and brought to the laboratory. Roots present in the soil cores were washed and scanned, and root images were obtained using a root length scanner using Winrhizo software (Aggarwal et al., 2006). The horizontal locations of soil cores were between -2.5 to 2.5 , 4.5 – 9.5 and 11.5 – 16.5 cm, respectively, for 0–15, 15–30 and 30–45 cm soil depth layers (Fig. 2). Mapping of the *RLD* distribution, both vertically and

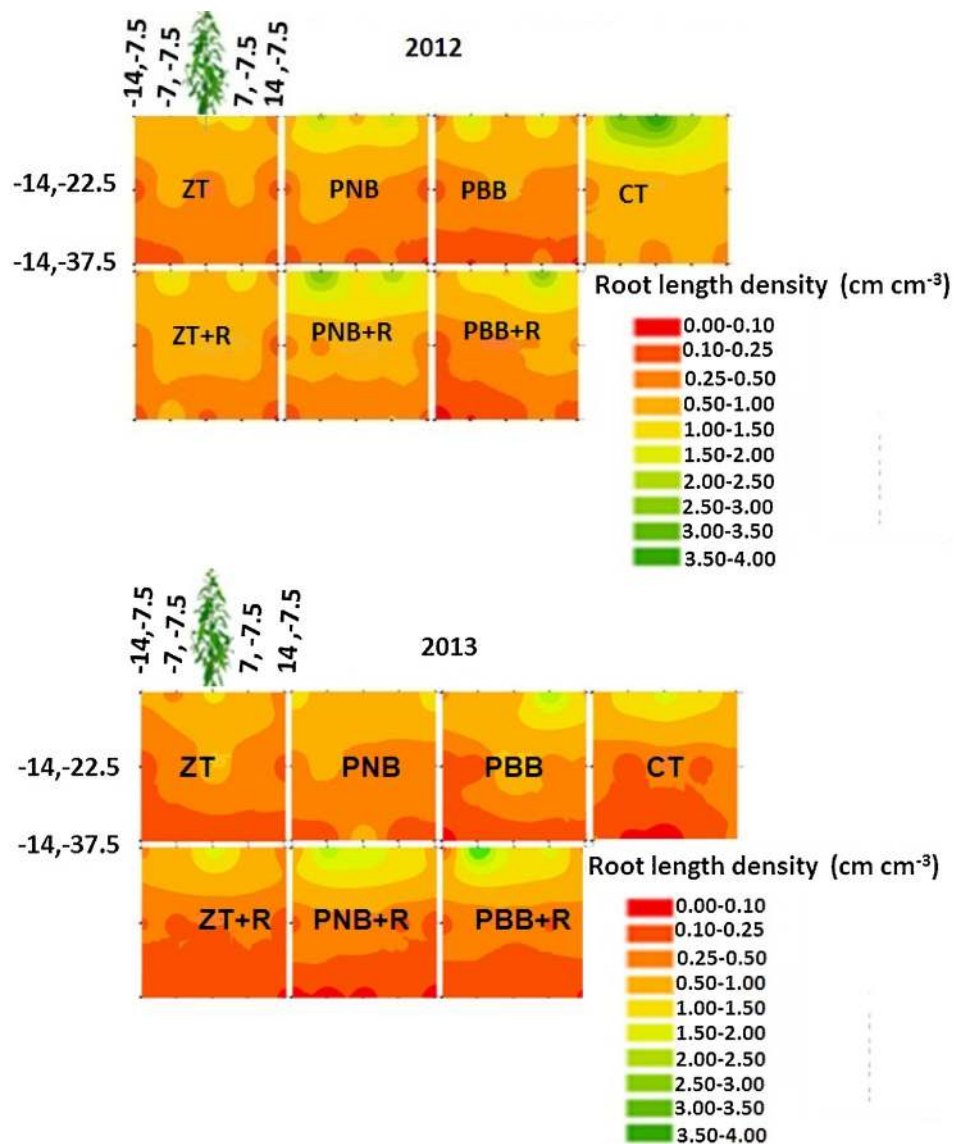


Fig. 2. Spatial distribution of the root length density of the cotton crop at the flowering stage under different soil conservation practices (ZT = Zero tillage; PNB = Permanent narrow bed; PBB = Permanent broad bed; CT = Conventional tillage; ZT + R = Zero Tillage + residue retention; PNB + R = Permanent narrow bed + residue retention; PBB + R = Permanent broad bed + residue retention) in 2012 (top) and 2013 (bottom). The z coordinates -7.5 , -22.5 , and -37.5 cm represent a center of 0–15, 15–30, and 30–45 cm soil sampling depths, respectively. Similarly, the x coordinates 0, 7, and 14 represent a center of sampling locations between -2.5 to 2.5 cm, 4.5 – 9.5 cm, and 11.5 – 16.5 cm, respectively.

horizontally, was performed through interpolation of measured data using the inverse distance weighting method. In addition, mean root diameter of the cotton crop for different treatments was also computed.

2.5. Leaf Area Index and photosynthetically active radiation (PAR)

Leaf Area Index ($\text{m}^2 \text{m}^{-2}$) data for all treatments were recorded using 1 m^2 quadrat from three locations in each plot at 30, 60, 90 and 120 DAS (Das et al., 2014) in 2012. A Point Quantum Sensor (Apogee; Model MQ-200) was used to measure incident and intercepted photo synthetically active radiation (PAR) by cotton canopy. PAR measurements ($\mu\text{mol m}^{-2} \text{s}^{-1}$) were taken above the canopy with the sensor facing the sky to account for received incident radiation (I_o') and with the sensor facing the canopy to account for reflected radiation from the canopy (I_r). The actual incident radiation (I_o) is the difference between I_o' and I_r . Measurements were also taken below the canopy, keeping the sensor just above the soil, but across the rows with the sensor facing upwards, for the transmitted radiation (I_t') through the canopy and for the emitted and/or reflected radiation from the soil (I_e). Thus, actual transmitted radiation (I_t) is the difference between I_t' and I_e . Three sets of measurements were recorded in each plot and averaged. The above measurements were taken on 30, 60, 90 and 120 DAS on clear days between 1100 and 1200 h IST, when disturbances due to leaf shading and solar angle were at their minimum. These measurements were used to derive fraction intercepted PAR (fIPAR):

$$fIPAR = \frac{I_o - I_t}{I_o} \quad (1)$$

The canopy fIPAR and LAI were related using following equation (Monsi and Saeki, 1953):

$$fIPAR = 1 - \exp(-\kappa \cdot LAI) \quad (2)$$

where κ is the canopy radiation extinction coefficient and LAI is the Leaf Area Index (Robertson et al., 2001). The κ was determined on 30, 60, 90 and 120 DAS from the measured values of fIPAR and LAI for each treatment. Values for fIPAR and LAI for each day after the start of simulation were interpolated between actual measurements by linear interpolation throughout the simulation period. The computed κ values were used for measurement of potential transpiration rates (T_{rp}).

2.6. Weather parameters and transpiration rate

Daily weather data (maximum and minimum temperatures, rainfall and pan evaporation) were recorded from the meteorological observatory adjacent to the experimental site. Transpiration rate $T_r(t)$ at a given time t is related to mean transpiration rate T_{rmean} using the following equations (Fayer, 2000):

$$T(t) = 0.24T_{rmean} \quad t < 0.264d, t > 0.736d \quad (3a)$$

$$T(t) = 2.75T_{rmean} \sin \left[\frac{2\pi t}{1day} - \frac{\pi}{2} \right] \quad t \in (0.264d, 0.736d) \quad (3b) \quad (3)$$

Hence, the maximum transpiration rate T_{rmax} (which occurs when $\theta = \pi/2$) is equal to $2.75T_{rmean}$

$$\text{or } T_{rmean} = T_{rmax}/2.75 \quad (4)$$

The maximum transpiration rate (T_{rmax}) was measured in the field using a porometer at ~ 1200 (because the peak transpiration rate occurs during this period) (Wang et al., 2007) on 45, 75 and 105 DAS.

2.7. Hydrus-2D model and its calibration

2.7.1. The Hydrus-2D model

The Hydrus-2D (Šimůnek et al., 2008) model is a Microsoft Windows based software package for simulating temporal variations in soil water content distributions and RWU. Hydrus-2D is a finite element model that numerically solves the Richards equation for saturated and unsaturated water flow. Root water uptake is included as a sink term that can be computed using the Feddes RWU Model (Feddes et al., 1978). Details about the model can be obtained from the Hydrus-2D technical manual (Šimůnek et al., 2011). Calibration of the Model was performed using data from 2012, whereas validation and simulation of different components of soil water balance were done for both years. Details of steps of calibration of the model along with the various input parameters required are discussed below.

2.7.2. Domain geometries and its discretization

Geometries characterizing the soil transport domain for different CA practices used in Hydrus-2D modelling are shown in Fig. S2 (Supplementary Information). A default value (2.2 cm) of the targeted finite element size, as suggested in the Hydrus-2D Model, was used for the spatial discretization and mesh generation (Supplementary Information, Fig. S3). Three observation points were inserted at (0, 7.5) (0, 22.5) and (0, 37.5) in the transport domain for the model to report continuous changes in SWCs with time. Calculated water contents at these three observation points were compared with experimentally measured water contents (that were measured near the base of the plant) in the 0–15, 15–30 and 30–45 cm soil layers, respectively.

2.7.3. Soil hydraulic properties

In the present study, the van Genuchten-Mualem model (Van Genuchten, 1980) was used to represent the water retention curve [$S_e(\Psi)$] and the unsaturated hydraulic conductivity function [$K(\theta)$]:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (5)$$

$$S_e = \left[\frac{1}{1 + (\alpha\psi)^n} \right]^m \quad (6)$$

$$K(\theta) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m} \right)^m \right]^2 \quad (7)$$

where, S_e is the effective soil water content, θ_s and θ_r are the saturated and residual water contents, respectively, K_s is saturated soil hydraulic conductivity, α is an inverse of the air-entry suction value (or bubbling pressure), n is a pore-size distribution index, l is a pore-connectivity parameter assumed as 0.5, and m is another parameter related to the pore size distribution and is equal to $1-1/n$. All the input parameters K_s , θ_r , θ_s , α and n were obtained experimentally.

A. Field saturated hydraulic conductivity (K_s): It was measured in the field using a Guelph Permeameter.

B. Residual soil water content (θ_r): The soil water content at permanent wilting point was taken as the θ_r .

C. Saturated soil water content (θ_s): The θ_s was taken as the porosity of soil, which was calculated from the bulk density, assuming the particle density 2.65 Mg m^{-3} .

D. Parameters m , n , and α : We determined soil water contents at 7 different water potentials and drew the soil water retention

(ψ - θ) curve. Then θ_p was determined using the following equation:

$$\theta_p = \frac{\theta_s + \theta_r}{2} \quad (8)$$

where θ_s and θ_r were saturated and residual water contents, respectively. Then the values of ψ_p were read (ψ_p was the value of soil water potential for the given value of θ_p , read from the ψ - θ curve). Then S_p (slope of the curve around point P with coordinates (θ_p , ψ_p)) values were calculated using the following equations:

$$\frac{d\theta}{d(\log h)} = (\ln 10)h \frac{d\theta}{dh} \quad (9)$$

$$S_p = \frac{1}{(\theta_s - \theta_r)d(\log h)} \frac{d\theta}{dh} \quad (10)$$

After computing S_p , m was calculated using following equations according to Van Genuchten (1980):

$$m = 1 - \exp(-0.8S_p) \quad (0 < S_p \leq 1) \quad (11)$$

$$m = 1 - \frac{0.5755}{S_p} + \frac{0.1}{S_p^2} + \frac{0.025}{S_p^3} \quad (S_p > 1) \quad (12)$$

n was computed from m using the relation (Van Genuchten, 1980):

$$n = \frac{1}{1 - m} \quad (13)$$

The α parameter (i.e. the inverse of the air-entry suction, bubbling pressure), was computed from ψ_p and m using the following equation:

$$\alpha = \frac{1}{\psi_p} \left(2^{1/m} - 1 \right)^{1-m} \quad (14)$$

2.7.4. Root water uptake (RWU) model

Root water uptake (RWU), a sink term in the Richards equation, was computed from the equation given below (Feddes et al., 1978):

$$S(\psi, x, z) = \alpha(\psi, x, z)S_p(x, z) = \alpha(p, x, z)b(x, z)T_p L_t \quad (15)$$

where the water stress response function $\alpha(\Psi, x, z)$ is a dimensionless function of the soil water pressure head (Ψ); $S_p(x, z)$ is potential root water uptake ($\text{cm}^3 \text{cm}^{-3} \text{d}^{-1}$); $b(x, z)$ is the normalized root water uptake distribution (cm^{-2}); T_p is the potential transpiration rate (cm d^{-1}); and L_t (cm) is the width of the soil surface associated with transpiration (Deb et al., 2013).

According to Feddes et al. (1978), α varied between 0 and 1, depending on soil water pressure head Ψ . It was assumed to be 0 at the soil water pressure head from saturation to -50 cm (P_0 = a value of the pressure head below which roots start to extract water from the soil) and then increased linearly between pressure heads of -50 to -200 cm. Optimal RWU was between pressure heads of -200 and -2000 cm (P_{opt} = a value of the pressure head below which roots extract water at the maximum possible potential transpiration rate). P_{2H} is the limiting pressure head, below which roots can no longer extract water at the maximum rate (assuming a potential transpiration rate of T_{p2H}) and P_{2L} is same as P_{2H} , but for potential transpiration rate of T_{p2L} . T_{p2H} and T_{p2L} are the maximum and minimum daily potential transpiration rates corresponding to the pressure heads of P_{2H} and P_{2L} . RWU then linearly decreases until it becomes zero at the wilting point, P_3 . The above values of the water stress response function, namely P_0 , P_{opt} , P_{2H} , P_{2L} and P_3 for the cotton crop were taken from the HYDRUS internal database.

The two-dimensional function $b(x, z)$ describing the spatial distribution of potential RWU over the root zone was obtained by normalizing the measured root length density data. Normalizing $b(x, z)$ ensures that the function integrates to unity over the flow domain. It is given by the following equation (Vrugt et al., 2001):

$$b(x, z) = \left(1 - \frac{x}{X_m} \right) \left(1 - \frac{z}{Z_m} \right) \exp \left(\frac{p_x(x - x^*)}{X_m} + \frac{p_z(z - z^*)}{Z_m} \right) \quad (16)$$

where Z_m and X_m are the maximum rooting depth and the maximum width of the root zone, respectively, and p_x , p_z , x^* and z^* are empirical parameters. These parameters were included to provide for zero RWU at $z = Z_m$ and $x = X_m$ and also to allow for a maximum RWU rate at a depth Z_0 ($0 < Z_0 < Z_m$) and width X_0 ($0 < X_0 < X_m$). Parameters p_z and p_x were set to unity for values of $z > z^*$ and $x > x^*$, whereas these were fitted values for $z < z^*$ and $x < x^*$.

The following inputs were required for determination of $b(x, z)$: the maximum rooting depth (a depth down to which RLD was $>0.25 \text{ cm cm}^{-3}$), the depth of maximum root water uptake (a depth down to which RLD was $>1.0 \text{ cm cm}^{-3}$), the maximum horizontal root spread (a horizontal distance on either side of the base of the cotton plant up to which RLD was $>0.25 \text{ cm cm}^{-3}$) and the horizontal maximum root water uptake zone (mean root diameter of tap root in cm). By choosing a tap root/primary root diameter as the horizontal extent of maximum root water uptake, simulations of RWU from the soil profile became symmetrical in shape, whereas other choices of computing this parameter gave unsymmetrical water uptake around the plant. Computation of T_{rp} is given in the next section. The width of the soil surface associated with transpiration (L_t , cm) was obtained by measuring the width of the canopy cover of 8 plants in each treatment.

2.7.5. Time-variable atmospheric boundary conditions

The Hydrus-2D Model requires daily rainfall, daily potential soil evaporation (E_p) and T_{rp} as inputs for defining the upper atmospheric boundary conditions. All weather parameters required for computation of daily reference evapo-transpiration (ET_0), including daily precipitation, maximum and minimum temperature, maximum and minimum relative humidity and pan evaporation rates, were recorded by the meteorological observatory located ~ 1.0 km from the experimental plots. For computing both these components, ET_0 was calculated using the FAO-56 Penman-Monteith equation (Allen et al., 1998) based on the weather data. The calculated ET_0 was multiplied by a crop coefficient (K_c) to estimate the evapo-transpiration of the cotton crop under standard well-watered, fertilized and disease-free conditions (ET_c).

For partitioning ET_c into E_p and T_{rp} , the following formula (Ritchie, 1972) was used:

$$E_p = ET_c \exp(-\kappa \cdot LAI) \quad (17)$$

where κ is the constant related to radiation extinction by canopy cover and was computed from $fIPAR$ and LAI data using Eq. (2).

2.7.6. Initial condition

The initial SWC of the profile for each simulation period was set as the SWC of the profile measured at the beginning of each simulation.

2.7.7. Boundary condition

The upper boundary of the soil domain was set at the atmospheric boundary and the lower boundary was set as the free drainage boundary. The vertical sides of the domain had no flux boundaries.

2.7.8. Validation of the model and simulation of root water uptake

For evaluating the accuracy of the output of the model, predicted values of SWC from observation nodes at (0, -7.5), (0, -22.5) and (0, -37.5) were compared with measured values of SWC of 0–15, 15–30 and 30–45 cm soil layers measured near the plants on 30, 40, 45, 80, 100 and 105 DAS in 2012 and 2013. The performance of the model was checked by computing the coefficient of determination (r^2) and the root mean squared error (RMSE) (Skaggs et al., 2004). The r^2 values describe the proportion of the total variance explained by the model. It varies between 0 (no correlation) and 1 (perfect correlation). The root mean squared error (RMSE) informs about the actual size of the errors and was calculated as:

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (P_i - O_i)^2 \right]^{0.5} \tag{18}$$

where P_i is the i^{th} predicted value, O_i is the i^{th} observed value, and N is the total number of observations. RMSE has the same units as O and P . The regression analysis, in the context of the sensitivity analysis, involves fitting a linear regression to the model output and, therefore, the standardized regression coefficients can be used as the direct measure of sensitivity (Saltelli et al., 2000). RWU of the 0–45 cm of soil profile on various days was simulated by inserting all the needed inputs in both years. The average relative error (AVE) was also calculated using the following equation (Zhou et al., 2007a,b):

$$AVE = \left[\frac{1}{N} \sum_{i=1}^N (P_i - O_i) \right] \frac{100}{O_i} \tag{19}$$

2.8. Statistical analysis

We analysed soil properties using Analysis of Variance (ANOVA) for a randomized block design. The Tukey's honestly significant difference test was used as a *post hoc* mean separation test ($P < 0.05$) using SAS 9.1 (SAS Institute, Cary, North Carolina, USA). The Tukey's procedure was used where the ANOVA was significant.

3. Results and discussion

3.1. Hydraulic parameters used for the model

The measured values of θ_r , θ_s , and K_s (in 2012) and computed values of the shape parameters (α , m and n) of the soil water characteristics curve for all treatments are presented in Table S1 (Supplementary Information). Results indicated that θ_r did not show significant variations among treatments. However, θ_s of the 0–15 cm layer was highest in the PNB + R treated plots ($0.44 \text{ cm}^3 \text{ cm}^{-3}$) and lowest in the ZT plots ($0.37 \text{ cm}^3 \text{ cm}^{-3}$). All soil

conservation practices had no impacts on θ_s in the 15–30 and 30–45 cm soil depth layers (Table S1; Supplementary Information). The K_s values of the 0–15 cm soil layer were higher in the plots with raised bed planting, in the PBB (144 mm d^{-1}) and PNB (188 mm d^{-1}) plots, than in the CT (102 mm d^{-1}) and ZT (59 mm d^{-1}) plots. Retention of crop residues in both bed planting systems increased K_s by 100% compared with CT. K_s values of the 15–30 and 30–45 cm soil depth layers did not vary much among treatments and were $< 100 \text{ mm d}^{-1}$.

K_s is highly dependent upon soil BD, porosity and the size, continuity and arrangement of pores. A higher estimated value of K_s in the CT plots compared with the ZT plots reflected higher porosity, since soil BDs of the 0–30 cm soil layer were lower in CT plots. Higher K_s values in the PNB and PBB plots compared with the CT plots were probably due to less settling of soils in the bed surface, as irrigation water was not applied directly to the beds. Flooding in the plots under CT probably caused more settlement of the loose surface soils, leading to lowering of K_s . In contrast, lateral slower movement of water from furrows to beds under PBB and PNB plots caused higher K_s . With retention of residues under both PNB and PBB plots, K_s values in the 0–15 and 15–30 cm soil depth layers increased further.

3.2. Measured parameters of the spatial root distribution

Only the vertical depth of 45 cm and the horizontal distance of 16.5 cm on either side of a cotton plant were used for root sampling, as preliminary studies indicated that this was the zone that contained $> 95\%$ of cotton roots at 90 DAS (flowering and bolling stage). Rogers and Prior (1992) and Zhao et al. (2010) reported similar results (the maximum root length density of cotton roots within a 45 cm layer) related to the root length density (RLD) distribution with soil depth for the growth stages of cotton.

Maps showing the vertical and horizontal distribution of the RLD were prepared using Arc GIS 9.3 (Fig. 2). Maps clearly showed that residue retention improved root parameters in the ZT, PNB and PBB plots. In the CT and bed planted plots (with or without residue), $\sim 65\text{--}70\%$ of roots resided within the 0–15 cm soil layer and $\sim 18\text{--}25\%$ resided within the 15–30 cm layer. In the ZT and ZT + R plots, the 0–15 and 15–30 cm soil layers contained ~ 50 and 30% of total roots, respectively. The mean RLD of the surface 0–15 cm soil layer was highest under CT (2.20 cm cm^{-3}) and decreased by 41, 57 and 61% in the PNB, PBB and ZT plots, respectively. Addition of crop residues resulted in decreased RLD (compared to CT plots) by 16, 40 and 60%, respectively. Thus, PNB + R, PBB + R and ZT + R plots had 43, 39 and 27% higher RLD than PNB (1.28 cm cm^{-3}), PBB (0.94 cm cm^{-3}) and ZT (0.69 cm cm^{-3}) plots, respectively.

More root growth in the CT plots than in the PNB and PBB plots was probably due to more water application by the flooding

Table 1
Measured average Leaf Area Indexes (LAI) of cotton ($\text{m}^2 \text{m}^{-2}$), fractional intercepted radiation (fIPAR), and radiation extinction coefficient (κ) during the simulation period (2012).

Treatments*	LAI ($\text{m}^2 \text{m}^{-2}$ of soil)				fIPAR				Radiation extinction coefficient κ			
	30	60	90	120	30	60	90	120	30	60	90	120
DAS = Days after sowing												
CT	0.17 ^b	0.45 ^b	1.96 ^c	2.76 ^c	0.17	0.28	0.64 ^b	0.79	1.13 ^a	0.73	0.52 ^a	0.56 ^a
PNB	0.17 ^b	0.44 ^b	2.78 ^b	3.39 ^b	0.17	0.27	0.77 ^a	0.85	1.07 ^{ab}	0.71	0.53 ^a	0.55 ^a
PNB + R	0.19 ^{ab}	0.47 ^{ab}	3.01 ^a	3.46 ^{ab}	0.18	0.27	0.77 ^a	0.85	1.03 ^b	0.68	0.49 ^{ab}	0.54 ^{ab}
PBB	0.17 ^b	0.44 ^b	2.92 ^{ab}	3.56 ^{ab}	0.17	0.27	0.77 ^a	0.84	1.10 ^{ab}	0.71	0.50 ^{ab}	0.52 ^{ab}
PBB + R	0.20 ^a	0.49 ^a	3.08 ^a	3.72 ^a	0.18	0.27	0.76 ^a	0.84	1.01 ^b	0.65	0.46 ^b	0.50 ^b
ZT	0.18 ^b	0.43 ^b	2.87 ^{ab}	3.40 ^{ab}	0.18	0.26	0.73 ^a	0.83	1.10 ^{ab}	0.69	0.45 ^b	0.52 ^{ab}
ZT + R	0.18 ^b	0.45 ^b	3.15 ^a	3.42 ^{ab}	0.18 ns	0.26 ns	0.78 ^a	0.84 ns	1.07 ^{ab}	0.67 ns	0.48 ^{ab}	0.54 ^{ab}

Values within a column with similar lowercase letters in superscripts are not significant at $P < 0.05$ according to the Tukey's HSD test. CT = Conventional tillage; PNB = Permanent narrow bed; PNB + R = Permanent narrow bed + residue retention; PBB = Permanent broad bed; PBB + R = Permanent broad bed + residue retention; ZT = Zero tillage; ZT + R = Zero tillage + residue retention.

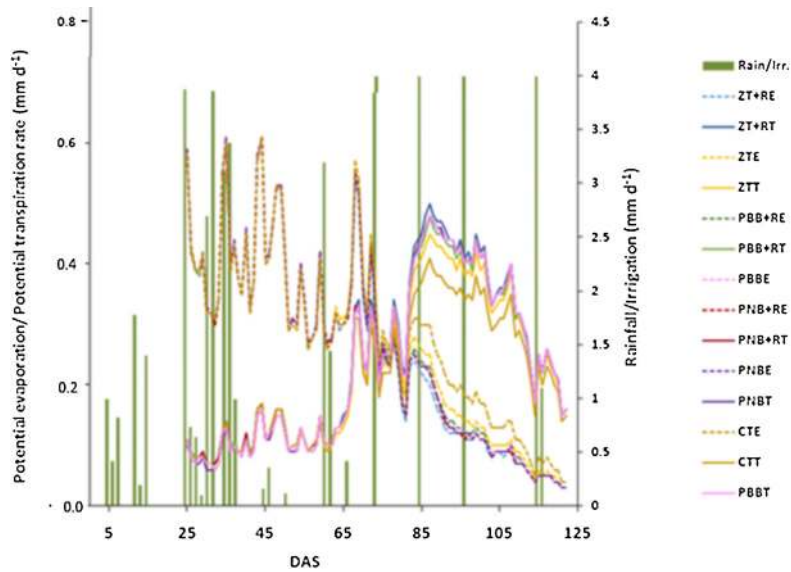


Fig. 3. Time-variable atmospheric boundary conditions for simulations of root water uptake and actual transpiration rate for different soil conservation practices (ZT = Zero tillage; PNB = Permanent narrow bed; PBB = Permanent broad bed; CT = Conventional tillage; ZT + R = Zero tillage + residue retention; PNB + R = Permanent narrow bed + residue retention; PBB + R = Permanent broad bed + residue retention). PE = Potential evaporation; PT = Potential transpiration; Irr = Irrigation; DAS = Days after sowing.

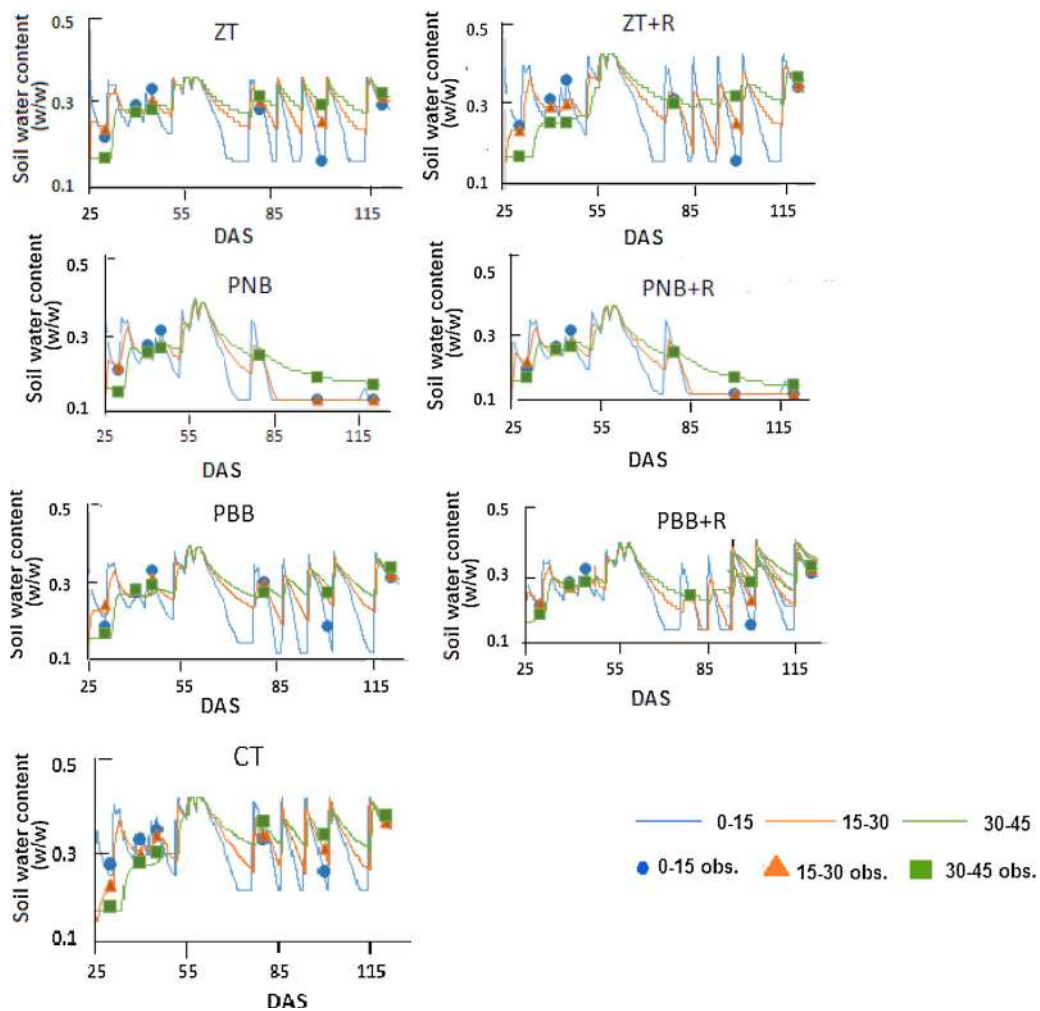


Fig. 4. Predicted soil water contents (SWCs) and measured SWCs at different soil depths under different soil conservation practices (ZT = Zero tillage; PNB = Permanent narrow bed; PBB = Permanent broad bed; CT = Conventional tillage; ZT + R = Zero Tillage + residue retention; PNB + R = Permanent narrow bed + residue retention; PBB + R = Permanent broad bed + residue retention; DAS = Days after sowing).

irrigation method in the CT plots than the furrow application of irrigation water in the PNB and PBB plots. Despite more water being applied (through flooding), the root growth in ZT plots was less compared with PNB and PBB plots, due to more surface sealing (which is the zone of maximum root growth) in the former treatment (ZT). Residue retention in soil surface improved *RLD* due decreased *BD*, along with an improvement in the *SWC*, the latter phenomenon occurred due to lower evaporation losses.

These maps were then used to determine root distribution parameters, such as the maximum rooting depth (a depth with *RLD* $>0.25 \text{ cm cm}^{-3}$), the depth of the maximum *RLD* (a depth with *RLD* $>1.00 \text{ cm cm}^{-3}$), the maximum rooting radius (a horizontal distance on either side of the root base up to which *RLD* was $>0.25 \text{ cm cm}^{-3}$) and the radius of the maximum root intensity (mean root diameter of the primary plant root) for computing $b(x, z)$ as described earlier (Vrugt et al., 2001). Among different treatments, the depth of the maximum *RLD* was least in the ZT (19.0 cm) and most in the CT (27.7 cm) plots. Compared with the CA plots (PBB+R, PNB+R and ZT+R), plots without crop residue retention (PBB, PNB and ZT) had shallower maximum *RLD* depths and thicker primary roots. Parameters p_x and p_z for computing $b(x, z)$ were chosen, such that *RWU* around the centre of the tap root became symmetrical.

3.3. Leaf Area Index

All soil conservation practices had a similar leaf area per unit area (m^{-2}) and these values were significantly higher than those for the CT plots (Table 1). A higher Leaf Area Index (*LAI*) in the soil

conservation practices than in the CT plots could be due to the compounded effects of many factors, such as an additional nutrient supply, decreased competition for resources due to a lower weed density, improved soil physical properties and water regimes, better radiation interception, water extraction, aeration and less evaporation in the soil conservation practices compared with the CT plots (Unger et al., 1998; Bhattacharya et al., 2012, 2013; Das et al., 2014). Soil structure affects crop yield through a complex of root-based mechanisms, that in turn affect above-ground biomass (Passioura, 2002). Continuous ZT with residue removal often lead to poorer soil structural quality (more compact) and lower crop yields (Lotfollah et al., 2014). Similar trends were also observed in this study as well (Das et al., 2014).

3.4. Fractional intercepted photo-synthetically active radiation (*fIPAR*) and radiation extinction coefficient (κ)

Fractions of incident *PAR* intercepted by a cotton plant canopy (*fIPAR* values) computed at 90 DAS were similar in the PNB, PBB and ZT plots (0.81–0.82) and 30% higher than in the CT plots (Table 1). With residue retention in the PNB and PBB plots, the magnitude of *fIPAR* increased by 7%. At 120 DAS, *fIPAR* was also least in the CT plots (0.84) and it increased by 12% in the PNB and PBB plots, and by 8% in the ZT plots. However, residue retention at this stage of the cotton growth did not significantly improve *fIPAR* compared to the residue removal plots. There was an increase in the magnitude of κ as crop growth progressed from 90 to 120 DAS. The results were similar to those reported by Milroy et al. (2001). Both at 90 and 120 DAS, κ values were higher in the PBB+R and PNB+R plots than in

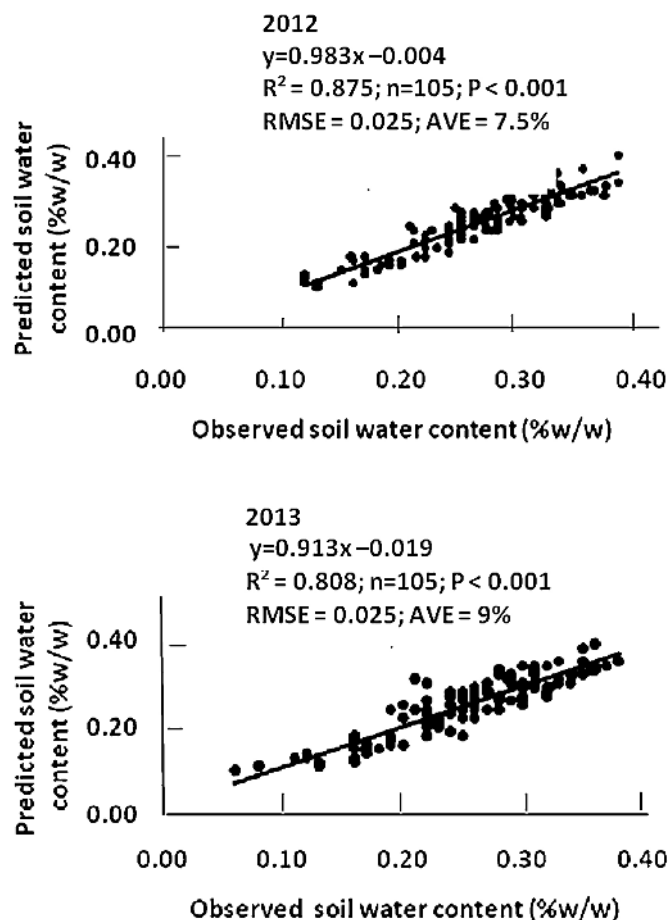


Fig. 5. Comparison of observed and simulated soil water contents (SWCs) under different soil conservation practices (*RMSE* = Root mean square error).

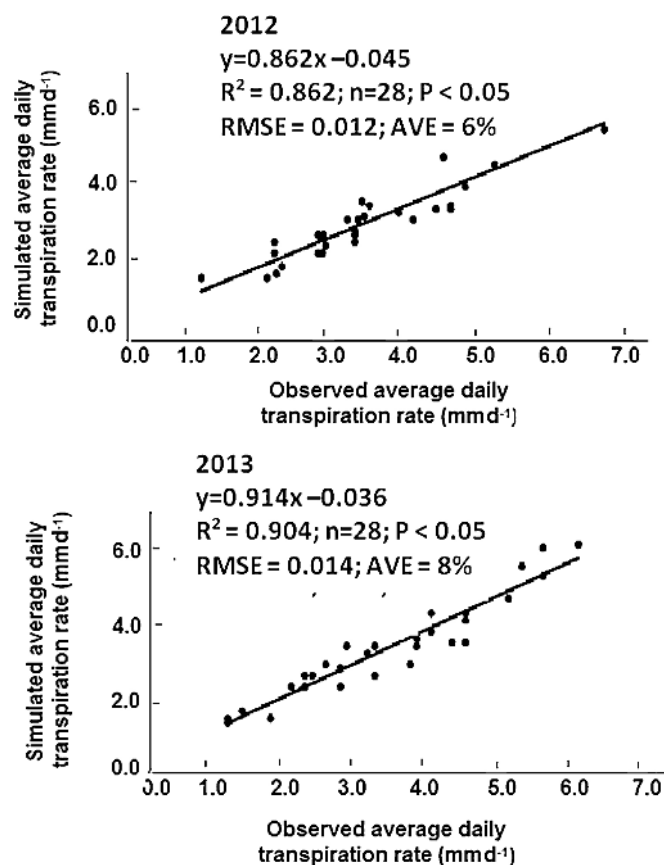


Fig. 6. Comparison of observed and simulated actual transpiration (mm d^{-1}) during the cotton growth in 2012 and 2013 (*RMSE* = Root mean square error; *AVE* = Average relative error).

remaining treatments. Widths of the plant canopy cover associated with transpiration measured at 100 DAS were also similar in the PNB, PBB and ZT plots (65 cm) and were 30% higher than in the CT plots. Residue retention further increased the width of canopy cover by 7%.

The partitioning of E_t into E_p and T_p was done to separate the productive (T_p) and unproductive (E_p) fluxes. Results clearly showed that after 78 DAS, E_p was higher and T_p was lower in CT plots compared to plots under soil conservation practices (Fig. 3). Cumulative E_p (CE_p) during the simulation period was 13.2–26.4 mm higher, whereas cumulative T_p (CT_p) was lower by the same amount in CT plots compared to plots with soil conservation practices. Residue retention in PBB and PNB increased CT_p slightly (0.7–2.5 mm). However, in the ZT+R plots, the magnitude of the CE_p reduction was 13.3 mm higher than in the ZT plots, which indicated the effectiveness of retained residues in decreasing evaporation rates in the ZT treatment (Derpsch, 2001).

3.5. Validation of the Hydrus-2D model to predict distributions of SWC

Figs. 4 and 5 compared SWC predicted by Hydrus-2D with those observed in all experimental plots. The results show that the model under-predicted the SWC of the soil profile. Comparison of simulated and observed SWC at different times during crop growth in 2012 and 2013 showed a relatively strong correlation (i.e. $R^2=0.88$; $n=105$; $P<0.001$ and 0.81 ; $n=105$; $P<0.001$), respectively, and the low RMSEs of 0.025 and $0.021 \text{ cm}^3 \text{ cm}^{-3}$, respectively. The AVE between simulated and measured SWC was ~ 7.5

and 9%, indicating that the model performed well in simulating soil moisture dynamics. Similar trends, although often with slightly weaker correlation coefficients, have been reported in many studies (Skaggs et al., 2004; Zhou et al., 2008; Lu et al., 2009; Buffon et al., 2012; Deb et al., 2013).

Fig. 6 compared mean daily transpiration rates predicted by the Hydrus-2D Model for different treatments with estimated values of mean daily RWU/transpiration rates obtained from Eq. (4), using the measured values of maximum transpiration rates ($T_{r,max}$) in all plots. Results also showed relatively strong correlations ($R^2=0.86$, $n=28$, $P<0.05$ and $R^2=0.90$, $n=28$, $RMSE=0.012$ and $0.014 \text{ cm}^3 \text{ cm}^{-3}$ and $AVE=6$ and 8% in 2012 and 2013, respectively) between measured and calculated mean daily transpiration rates under all treatments.

3.6. Root water uptake simulations

Actual root water uptake (mm day^{-1}) under different soil conservation practices during the 2013 simulation period (Fig. 7) also showed more daily water uptake by roots in both bed systems compared with CT and ZT systems, although the amount of water applied in the former treatments was less. The spatial distribution (and thus a depth-wise contribution of different soil layers) of RWU on 112 DAS is presented in Fig. 8. It was observed that in the ZT plots, the contribution of sub-surface layers to RWU was less, because of less root penetration to depth. In CT plots, both surface and sub-surface layers contributed to cumulative RWU, but the rates of RWU were less

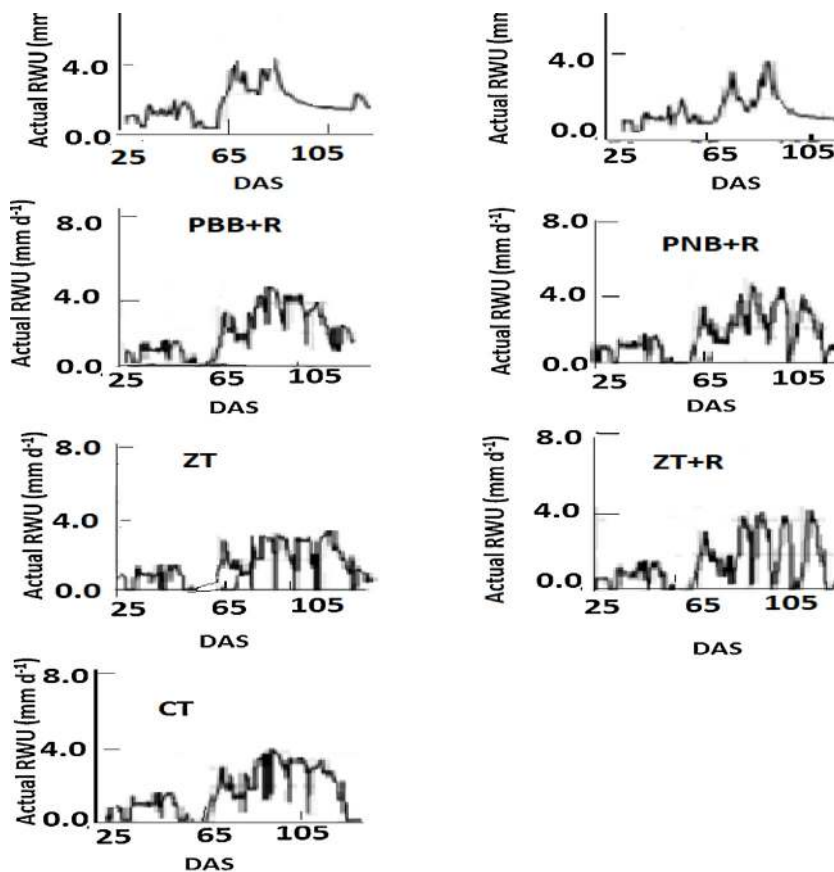


Fig. 7. Simulated actual root water uptake (mm d^{-1}) (vertical axis) versus DAS (days after sowing) (horizontal axis) for different soil conservation practices (PBB = Permanent broad bed; PNB = Permanent narrow bed; PBB+R = Permanent broad bed + residue retention; PNB+R = Permanent narrow bed + residue retention; ZT = Zero tillage; ZT+R = Zero tillage + residue retention; CT = Conventional tillage) during the 2013 simulation period.

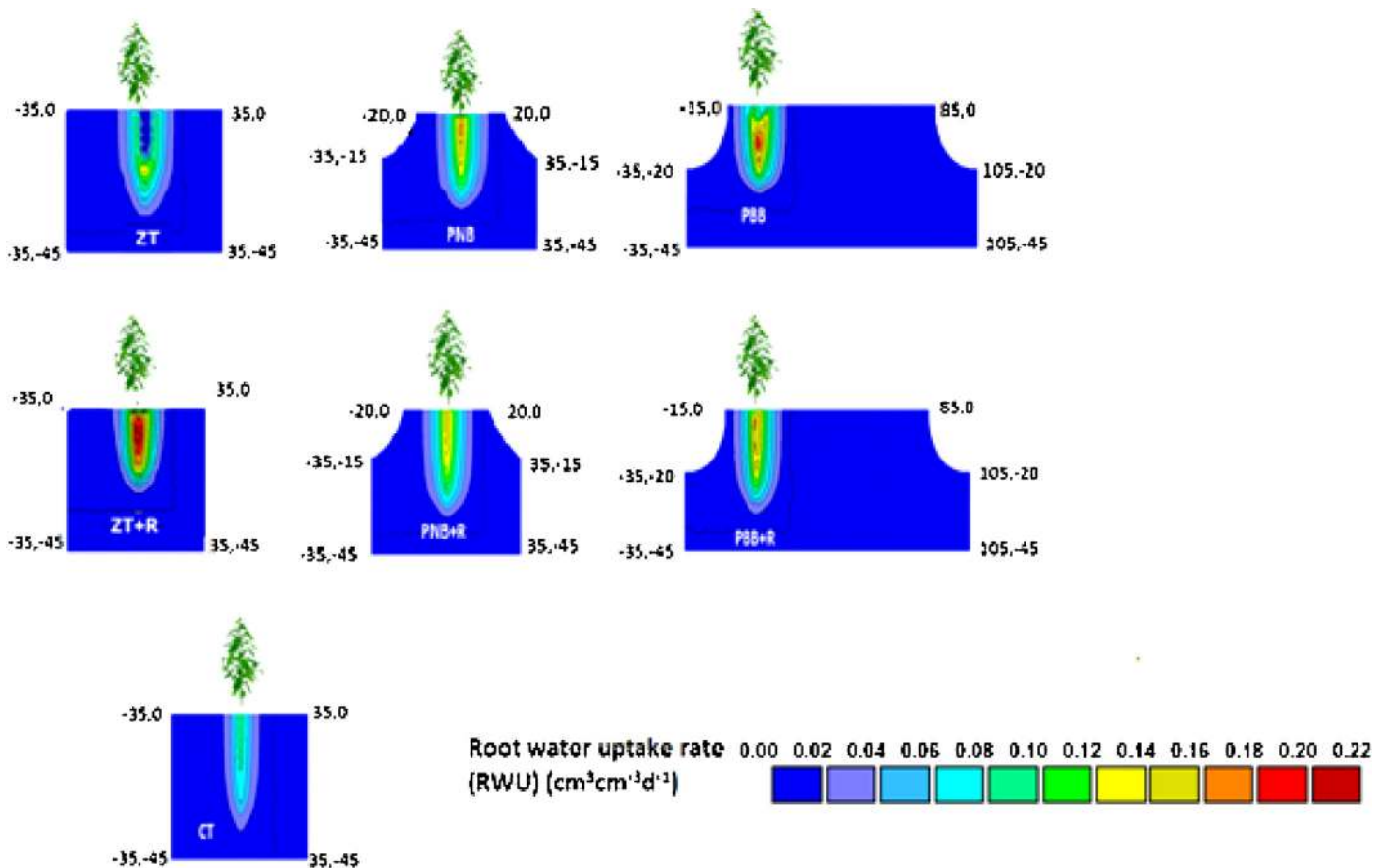


Fig. 8. Root water uptake rates (RWU) ($\text{cm}^3 \text{cm}^{-3} \text{d}^{-1}$) by cotton from 0 to 45 cm of the soil profile on 112 DAS in year 2012 under different soil conservation practices (ZT = Zero tillage; ZT + R = Zero Tillage + residue retention; CT = Conventional tillage; PNB = Permanent narrow bed; PNB + R = Permanent narrow bed + residue retention; PBB = Permanent broad bed; PBB + R = Permanent broad bed + residue retention). Vertical and horizontal directions represent the Z and X axes of the soil domain. For more detailed information about the dimensions of soil domains and planting geometries of different CA treatments refer to Fig. S2 (Supporting Information).

compared with other treatments. This was mainly because of higher water losses through evaporation in CT (Fig. 3). In both PBB and PNB plots, the contribution of surface layers was greater, and residue retention improved total water uptake by improving water uptake from deeper layers. The reasons for the highest cumulative RWU flux in the PBB + R plots are probably linked to the better soil physical environment, maximum root proliferation, maximum radiation interception leading to higher LAI and hence maximum T_{rp} . All these factors contributed to providing a better microclimate in the PBB + R plots than in the CT and residue removal plots. Thus, better observed RWU in the plots under PBB + R than in the CT and residue removal plots probably contributed to realizing greater crop productivity in the former treatment compared with other plots (Das et al., 2014).

Sensitivity analysis of model outputs to soil hydraulic parameters was also performed to understand changes in cumulative root water uptake (CWU; an output variable of the Hydrus-2D model) due to changes in the model input parameters (θ_r , θ_s , n , α , K_s , and l) for plots under CT during the 90–120 DAS period. Results showed that when the input parameter n changed by $\pm 10\%$, CWU values changed from -7.83 to $+6.85\%$. Similar changes in θ_s produced changes in CWU from -5.31 to $+3.18\%$; in α from -1.12 to $+2.30\%$; in θ_r from -0.44 to $+0.77\%$; in K_s from -0.59 to $+0.29\%$, and in l from -0.15 to $+0.20\%$. Similar results with a little different trend were previously reported by Rocha et al. (2006). Rocha et al. (2006) indicated that the most sensitive soil hydraulic parameter was the shape factor n , followed by θ_s , K_s , θ_r , and α , with l being the least sensitive.

3.7. Soil water balance studies

The results of simulated soil water balance components clearly indicated that cumulative RWU (transpiration) values for the ZT (143 mm) and CT (157 mm) plots were significantly lower than for the PBB (188 mm) plots (Table 2). Retention of crop residues in PBB, PNB and ZT treatments significantly improved cumulative RWU values. Similarly, cumulative evaporation (CE) from soils under different treatments were in the following order: PNB (278 mm) > PBB (245 mm) > CT = ZT (222 mm). Retention of crop residues in these conservation treatments significantly decreased CE. Among all treatments, PBB + R had the highest cumulative RWU (226 mm) and lowest CE (180 mm). Cumulative drainage from plots under PNB was 50% less than from CT plots (172 mm). The apparent reason for less drainage in both bed systems was mainly due to less applied irrigation, as well as more evaporation from the porous surface of both systems. It was also evident that both initial and final SWC values of the profile under CT were highest and these were significantly higher than in the PBB and PNB plots with or without residues, mainly because the amounts of irrigation water applied to CT was more than in both bed treatments.

4. Conclusions

To our knowledge, this study is the first global attempt to test and validate the Hydrus-2D Model for simulating RWU under CA. Higher RWU was observed in plots under PBB and PNB compared with CT (farmers' practice) and ZT plots, due to less

Table 2
Soil water balance components computed for different simulation periods during cotton growth in 2012 using Hydrus-2D.

Treatments	DAS	CRWU (mm)	CE (mm)	CD (mm)	RF/IRR (mm)	Initial SWC (mm)	Final SWC (mm)
CT	25–48	20.8	79.7	0.00	150.2	87.3	132.8
	49–77	31.1	71.4	150.0	232.6	146.8	155.7
	78–122	115.2	70.4	21.9	189.6	175.2	156.3
	Total	157.0 ^{cd}	221.6 ^c	171.9 ^a	572.4	409.3 ^a	444.8 ^a
PBB	25–48	23.0	90.0	2.60	150.2	64.0	102.2
	49–77	44.1	80.0	150.0	232.6	122.7	121.1
	78–122	121.3	75.0	16.0	189.6	155.0	98.0
	Total	188.4 ^{bc}	245.0 ^b	168.6 ^a	572.4	341.7 ^b	321.3 ^c
PBB + R	25–48	24.5	70.0	7.40	150.2	66.5	128.6
	49–77	53.7	60.0	132.3	232.6	128.6	116.2
	78–122	147.5	50.0	10.2	189.6	166.2	138.9
	Total	225.8 ^a	180.0 ^d	149.9 ^b	572.4	361.3 ^b	383.7 ^{bc}
PNB	25–48	20.0	91.9	1.4	150.2	60.1	104.5
	49–77	29.6	140.0	121.4	232.6	112.3	120.0
	78–122	113.0	45.7	0.9	189.6	112.3	64.5
	Total	162.6 ^{cd}	277.6 ^a	123.6 ^c	572.4	284.7 ^c	289.0 ^c
PNB + R	25–48	26.8	93.1	2.7	150.2	64.0	115.6
	49–77	33.3	123.9	81.4	232.6	101.2	132.2
	78–122	137.5	36.0	1.0	189.6	119.1	68.0
	Total	197.6 ^b	25.30 ^b	85.1 ^d	572.4	284.3 ^c	315.8 ^c
ZT	25–48	17.4	87.1	1.7	150.2	72.6	128.4
	49–77	26.0	75.9	120.0	232.6	128.4	142.4
	78–122	100.0	59.7	42.9	189.6	143.3	137.9
	Total	143.4 ^d	222.7 ^c	150.0 ^b	572.4	344.3 ^b	408.6 ^b
ZT + R	25–48	19.6	81.0	0.0	150.2	72.8	129.3
	49–77	29.2	77.3	139.0	232.6	129.3	149.1
	78–122	125.3	48.0	14.3	189.6	149.1	122.8
	Total	174.1 ^c	206.3 ^{cd}	153.3 ^b	572.4	351.2 ^b	401.2 ^b

DAS = Days after sowing; CRWU = Cumulative root water uptake; CE = Cumulative evaporation; CD = Cumulative drainage; RF/IRR = Rainfall/Irrigation; SWC = Soil water content.

CT = Conventional tillage; PBB = Permanent broad bed; PBB + R = Permanent broad bed + residue retention; PNB = Permanent narrow bed; PNB + R = Permanent narrow bed + residue retention; ZT = Zero tillage; ZT + R = Zero tillage + residue retention.

drainage and better soil physical environment causing more root growth, along with more radiation interception. All these factors led to more biomass and hence more transpiration and lower evaporation rates in PBB and PNB plots compared with CT and ZT plots. Residue retention in the PNB, PBB and ZT plots (CA practices) further improved RWU values. Hence, this study explains the reason (physical processes in the soil and atmosphere) behind greater cotton productivity under PBB + R (Das et al., 2014). Among all soil conservation practices, PBB + R plots used less water and had higher root water uptake, and increased productivity and water use efficiency. Hence, PBB + R is a better environmental protection technology than the farmers' practice and is recommended under the cotton-wheat system in the region and similar agroecologies.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.agee.2017.02.028>.

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