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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.) fieldsunder 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 *SWC*s. 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.


## 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 (*SWC*s) 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 $\leq\pm3\%$). 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$^{-1}$, $KMnO_4$ oxidizable N 182.3 kg ha$^{-1}$, 0.5 M $NaHCO_3$ extractable P 23.3 kg ha$^{-1}$, and 1 N $NH_4OAc$ 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