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Modelling soil water dynamics and crop water use in a soybean-wheat rotation under chisel tillage in a sandy clay loam soil

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ABSTRACT

Mechanical chiseling disrupts the sub-surface compaction often found in agricultural soils, and modifies soil physical condition conducive to root growth. However, the effect is transitory and therefore, the impact on soil hydraulic characteristics and consequently on water dynamics must be precisely quantified for effective technology-targeting. In this study, Hydrus-2D was used to describe the soil water change, root water uptake and profile water balance components under different time lags after chiseling. The input parameters were collected from a 2-year field experiment with soybean-wheat crops in rotation on a sandy loam soil in the experimental farm of the ICAR-Indian Agricultural Research Institute, New Delhi. The chisel treatments were residual (RS), repeated (RC) and no chisel (NC). Greater root water uptake in RS and RC compared to the NC could be attributed to marginally higher leaf area index and fIPAR in chiseled plots along with greater depth and spread of roots. Model simulated soil water content was in good agreement with observed data in the first year of rotation. The model was further validated by comparing the simulated and observed values of crop transpiration with $R^2 = 0.85$ and 0.72 ($p < 0.001$) in soybean and wheat crop, respectively in the following year. Simulated field water valance components indicated 50–70 mm higher seasonal transpiration by the crops. Chisel plots had significantly higher yield and water use in 1st year soybean-wheat rotation, but the effect of chisel became marginal in the 2nd year rotation. Soil water content profile indicates higher plant-available water in chiseled plots. In view of the cost of chiseling and the marginal benefits obtained till 2nd tear of crop rotation, chiseling once in 2–3 years may be recommended for the sandy loam soils under the semi-arid climate condition.

1. Introduction

The sub-surface compaction caused by wheel traffic and natural forces essentially affects the soil physical properties and crop performance. Sub-surface compaction in cultivated soil has been widely reported in India (Aggarwal et al., 2006; Kumar et al., 2014; Aggarwal et al., 2015), Australia (Hamza and Anderson, 2003; DAFWA, 2006), Japan (Ohtomo and Tan, 2001), Russia (Bondarev and Kuznetsova, 1999) and New Zealand (Russell et al., 2001). The critical values of bulk density to restrict root growth could be 1.6 Mg m^{-3} (McKenzie et al., 2004), although it varies with soil type. In terms of soil resistance-to-penetration (a composite bulk density-soil water content parameter), the value is 2 MPa (Silva et al., 2008; Lima et al., 2012), beyond which root growth is severely restricted. Mechanical impedance > 2.8 MPa below 10–15 cm depth was reported in 35 rice-growing locations in South and South-East Asia (Hasegawa et al., 1985). Sub-surface compaction were reported extensively in India with soil penetration resistance values of 1.2–1.5 MPa in soybean in a deep clay soil in central India (Hati et al., 2014), > 2.5 MPa in puddled rice in a sandy loam soil in north-west India (Kukal and Aggarwal, 2003), 2.0–2.5 MPa in maize in a sandy loam soil in north India (Saha et al., 2010; Parihar et al., 2016), and elsewhere. However, roots may penetrate through the large-sized pores, even when the bulk density is sufficiently high to physically limit the root growth and development (McKenzie et al., 2009; Valentine et al., 2012; Kautz et al., 2013).

Chisel ploughing is a key mechanical way to break the compact subsoil layer. It reduced the bulk density, increases infiltration, thus increasing the water storage in the soil profile and improves aeration in the root zone. Following decades of research under the ICAR-AICRP programme, chiseling has been recommended for a number of Indian soils to reduce the mechanical impedance and improve the productivity of crops (Painuli and Yadav, 1988; Ghildyal and Gupta, 1991).

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However, chiseling effects are transient (e.g. Busscher et al., 2002) and in subsequent time, fine soil particles start filling the soil pores following rainfall, and the bulk density gradually increases (Rao et al., 1998; Allen and Musick, 2001). This will slowly but surely decrease the vertical saturated hydraulic conductivity and maximize the surface runoff (Kincaid, 2002). There are reports of minor effect of chiseling attributed to highly variable rainfall intensities between chisel-ploughing and the start of planting (Keim and Faiers, 1996; Moriasi et al., 2007). Moreover, chiseling involves cost of operation and is also energy-intensive, making it necessary to determine the frequency of its operation to gather the maximum benefits.

Spatial distribution of root length and soil water status affect soil water extraction by roots and its partitioning over depth (Lascano and Van Bavel, 1984; Feddes and Raats, 2004; de Jong van Lier et al., 2013). Quantifying the dynamics of water flow in the continuum of soil, water, air and roots is essential for optimizing the soil and water management practices, as it controls the partitioning of infiltrated rain or irrigation water into soil evaporation, plant transpiration and drainage (Wang and Smith, 2004; Roger-Estrade et al., 2009). Precise description of layer-specific soil hydraulic properties viz., soil water retention [$\theta(h)$] and hydraulic conductivity [$K(h)$] functions is required to model soil water dynamics. In this study, we hypothesized that (i) a reduction in sub-surface compaction would activate root growth and water uptake; and (ii) deep drainage would reduce due to higher profile water storage through chiseling. To test the hypothesis, we have used the Hydrus-2D (Šimůnek et al., 2008), which is a process based model for simulating two-dimensional water movement, by solving the Richard's equation for unsaturated flow in soil at a depth intervals. The model describes soil water flow through soil-plant-atmosphere continuum and thereby it is possible to simulate soil water balance components. Hydrus model has been widely used since its introduction, for unsaturated soil media for various applications including soil water balance (e.g. Mermoud et al., 2005), groundwater recharge (e.g. Han et al., 2015), root water and nutrient uptake (e.g., Šimůnek and Hopmans, 2009) and soil temperature (e.g. Dahiya et al., 2007). In this study, the coefficients for estimating the water balance were calibrated with field-observed values. Radiation extinction coefficients of crop at different growth stages were computed from measured intercepted photosynthetically active radiation to describe the time-variable boundary conditions of potential evaporation and transpiration rates, and the root parameters were monitored in the field at various growth stages. Chiseling reduces soil strength and modifies soil pore size distribution, affecting soil water content and root uptake. Hydus-2D simulates the change distribution within the root-zone, and therefore the differences between the chiseled and non-chiseled plots can be suitably described.

2. Materials and methods

2.1. Study area

Field experiments with soybean-wheat crop rotation were conducted at the experimental farm of the ICAR-Indian Agricultural Research Institute, New Delhi (28°38′23″ N and 77°09′27″ E; 228.6 m amsl). The climate is subtropical, semiarid and is characterized by hot dry summer and cold winter. The mean annual rainfall is 769.3 mm, of which 75% is received between July and September. The soil is Typic Haplustept, sandy loam in texture at surface (0–15 cm) and sandy clay loam at subsurface layers, moderately alkaline in pH (7.9–8.3), low in soluble salt content and medium (0.41–53%) in organic carbon content (Pradhan et al., 2010).

The chiseling tillage treatments were residual (RS) (chiseling on 28.5.2011), repeated (RC) (chiseling on 28.5.2011 and 20.5.2013), and no chisel (NC) as control, laid in a completely randomized block design with 6 replications. Net plot size of each treatment was 7.5 m × 8 m. Chiseling operations were carried out to a depth of 30–40 cm at 50–120 cm spacing. Soybean crop (variety Pusa 9814) was sown on July 9 and 4 and harvested on November 2 and October 29 in year 2013 and 2014, respectively. The crop was completely rainfed in 2013 but in 2014, it required three irrigations on 34, 74 and 96 days after sowing (DAS) due to prevailing long dry period. Wheat (variety PBW-502) was sown on November 26 and 21 and harvested on April 20 and 23 in 2013–14 and 2014–15, respectively. A total of 4 irrigations (CRI, late tillering, booting and dough stages) were given to the crop. Recommended agronomic practices and crop protection measures were followed.

2.2. Observations

For each layer (0–15, 15–30 and 30–45 cm), undisturbed soil cores (100 cm^3; n = 12) were used to determine water contents (θ) at −1, −3, −5 and-10 kPa matric suction (ψ) by using hanging water column and at −20, −33, −100, −500 and −1500 kPa by using pressure plate apparatus (Soil Moisture Equipment Corporation). The measured soil water content values were used to derive the van Genuchten parameters (van Genuchten, 1980). The in situ soil water content was monitored through gravimetry (0–15 cm), and Neutron probe (CPN-503 DR Hydroprobe, Campbell Pacific Nuclear International Inc., USA; 15–30, 30–45, 45–60 and 60–75, 75–90 and 90–120 cm layers). Field-saturated hydraulic conductivity (K_{fs}) was determined at 0–15, 15–30 and 30–45 cm soil layers by using Guelph Permeameter (GP) (Soil Moisture Equipment Corporation, Santa Barbara, CA, model no. 2800).

Leaf area index (LAI) was measured on 45, 75 and 105 DAS using Plant Canopy Analyzer (LAI-2000, LI-COR make) following the standard procedure. A quarter-view cap was placed on the sensor to exclude the operator, and the rest of the hemispherical view was used to make LAI observations. Multiple LAI readings (minimum 5) at different locations within a plot were averaged to obtain the LAI of that plot. A Point Quantum Sensor (LI-191, LI-COR) was used with an integrator (LI-250A, LI-COR) for measuring the photosynthetically active radiation (PAR) at the same time when LAI observations were taken. Three set of measurements were recorded in each plot and averaged. All PAR and LAI observations were taken on clear days between 11:30 and 12:30 h when disturbances due to leaf shading and solar angle were the minimum. The fraction Intercepted PAR (fIPAR) was calculated as

$$\mathrm{fIPAR} = \frac{I_0 - I_t}{I_0} \tag{1}$$

where I_0 and I_t are the incident (top of canopy) and transmitted (through canopy) radiation.

The canopy fIPAR and LAI were related using the following equation

$$\mathrm{fIPAR} = 1 - \exp(-k \times \mathrm{LAI}) \tag{2}$$

where, k is the canopy radiation extinction coefficient [the slope of the relationship between ln(1- fIPAR) and LAI; Saha et al., 2015] with intercept at zero.

A root auger (15 cm high and 7 cm in diameter), was used to collect the root samples at 45, 75 and 105 DAS. The plant was cut just over the soil surface and the auger was pushed vertically for 0–15, 15–30, 30–45 and 45–60 cm depth increments. Cores were washed to separate the roots from soil particles and roots were dried at 4°C. Roots were scanned by using a root length scanner and root length, volume, surface area densities and average diameter were obtained in each crop for each soil depth.

Daily maximum and minimum temperatures, rainfall and pan evaporation data were recorded from the agrometeorological observatory adjacent to the experimental site. The transpiration rate T(t) of the crop at a given time t is related to the daily transpiration rate $T_{average}$ through following equation (Fayer, 2000):

$$T(t) = 0.24 * T_{average} \qquad 0.736d < t \check{\ } 0.264d \tag{3}$$