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The effects of mulch and irrigation management on wheat in Punjab, India—Evaluation of the APSIM model

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ABSTRACT

With increasing interest in retaining crop residues on the soil surface, there is a need to evaluate their short- and long-term effects on crop yield and water and fertilizer requirements. Therefore, research on the interactions between residue and irrigation management on wheat crop performance and water use was initiated, using the dual approach of field experiments and crop modelling. This paper presents the results of a comprehensive evaluation of the APSIM model for its ability to simulate the effects of mulch and water management, and their interactions, for wheat in Punjab, India. The model was evaluated for its ability to predict crop development, grain yield, biomass production over time, soil water dynamics, daily soil evaporation (Es), total evapotranspiration (ET) and water productivity (WP_{ET} kg ha^{-1} mm^{-1}), using two years of data from field experiments at Ludhiana, Punjab. The model predicted grain yield adequately, with coefficients of determination (r^2) of 0.91 and 0.81 with and without mulch, respectively, and prediction of total biomass was even better, with r^2 of 0.99 and 0.92. The corresponding absolute RMSE values were 433 and 550 kg ha^{-1} for grain yield (means 4100 and 3800 kg ha^{-1}) and 300 and 800 kg ha^{-1} for total biomass (means 10,200 and 9300 kg ha^{-1}). However, grain yield was underpredicted (by 600–1000 kg ha^{-1}) in treatments where the crop was subjected to water deficit stress, even though simulation of soil water dynamics, and the effect mulch on soil water content, was generally very good. The model accurately predicted total crop seasonal evaporation and the effect of mulch; however, daily Es was poorly simulated. APSIM does not attempt to capture the soil temperature driven effect of mulch on crop phenology. The evaluation shows that APSIM is suitable to use for wheat under the conditions of north-west India. However, additional model processes that capture the effects of mulch on crop development and growth, as driven by soil temperature, are needed to help design intensive cropping systems to optimise land and water productivity. The ability to better simulate crop performance under conditions of water deficit is also needed to help determine irrigation management strategies that minimise irrigation input while maintaining yield.

1. Introduction

Irrigated wheat is grown in rotation with rice on 2.6 Mha in the intensive rice–wheat system of Punjab in north-west India (GOP, 2006). However, the sustainability of the rice–wheat system is threatened by declining soil fertility and groundwater depletion (Humphreys et al., 2010; Ladha et al., 2007). The rice–wheat system also causes serious air pollution as combine harvesting of rice leaves a mixture of loose and anchored residues in the field which require burning to enable timely wheat establishment. Therefore, there has been increasing pressure to find ways of establishing the wheat crop in the rice residues. This has led to the development of new sowing machinery, the Happy Seeder (Sidhu et al.,2007, 2008), which enables direct drilling of wheat with full rice residue retention. In addition to reducing air pollution as a result of avoidance of burning, surface retention of the rice residues offers many potential benefits including improved soil physical, chemical and biological properties, and reduced soil evaporation (Es) (Yadvinder-Singh et al., 2005). However, the effect of surface residue retention on crop performance and water use is dependent on soil type, weather conditions and amount of residue. Therefore, the inclusion of surface residue retention in the cropping system requires greater knowledge of its effects on crop performance and nutrient and water dynamics on a long-term basis. Recently, there have been several field studies which focus on the effect of mulch on wheat yield in north-west India (Balwinder-Singh et al., 2011; Chakraborty et al.,

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2008; Sharma et al., 2008; Sidhu et al., 2007; Yadvinder-Singh et al., 2008). However, the results of these studies are season- and site-specific, short-term, and provide few insights into the mechanisms by which mulch affects yield and water availability and requirement.

Cropping system models are useful tools for studying the soil–crop–atmosphere system as affected by management (e.g. sowing date, fertilizer application, irrigation scheduling) and weather variability. They can also be used to extrapolate results to other sites and climates over space and/or time. To date, various crop models have been successfully evaluated and applied to individual crops including rice and wheat, and occasionally cropping system models have been applied to simulate crop sequences, in north-west India (e.g. Arora et al., 2007; Jalota and Arora, 2002; Jalota et al., 2006; Timsina et al., 2008). However, there are no published data on the performance of crop models in simulating the effects of surface residue retention on crop performance, nor its implications for irrigation management. The APSIM (Agricultural Production System Simulator) cropping system model allows simulation of residue and irrigation management on crop performance, water dynamics, soil organic carbon (C) and soil nitrogen (N) on a daily basis (Keating et al., 2003) for individual seasons or crop sequences over one to many years.

APSIM has been validated and successfully used for wheat over a broad range of soils and climates in various part of the world (e.g. Asseng et al., 1998, 2000; Keating et al., 1995, Meinke et al., 1998; Yunusa et al., 2004). However, it has not been tested in the rice–wheat system of the Indo-Gangetic Plains (IGP), India's major wheat growing region. Moreover, the APSIM module SURFACE ORGANIC MATTER, which simulates the dynamics of surface residues and their influence on the components of the water balance, has not been evaluated for its ability to simulate the effects of surface residue retention on detailed dynamics of Es. Before a model can be used to help determine optimum crop and cropping system management, it must be parameterised and validated for the environments and management practices of interest. Therefore this paper presents the results of the parameterisation and evaluation of APSIM for wheat, established in bare soil or rice residues, with a range of irrigation scheduling treatments, in Punjab, India. The objective was to determine the level of confidence with which APSIM could be used for subsequent simulation studies to examine the effects of surface residue retention and irrigation management, and their interactions, on crop performance, water use and water productivity.

2. Materials and methods

2.1. APSIM model (v. 5.1)

APSIM is a simulation modelling framework that enables sub-models to be linked to simulate agricultural system performance. In simulating wheat crops, the four modules used are WHEAT, SOILWAT2, SOILN2 and SURFACE ORGANIC MATTER. The WHEAT crop module simulates the development, growth, water and N uptake, crop N concentration, stresses (water deficit, N deficit, aeration deficit) and response of the crop to the stresses (Keating et al., 2001). The WHEAT module is based on CERES Wheat (Jones and Kiniry, 1986; Ritchie et al., 1985) but with modifications (Asseng et al., 1998; Probert et al., 1995; Wang et al., 2003; Huth, unpublished).

The soil water module (SOILWAT2) is a cascading water balance model based on the water balance models in CERES and PERFECT (Probert et al., 1998; Littleboy et al., 1992). Enhancements to the module over these models are described in Asseng et al. (1998) and Keating et al. (2003). Soil evaporation in SOILWAT2 is assumed to take place in two stages, following the approach of Ritchie (1972). These two stages are described through the use of two parameters: U and cona. The parameter U represents the amount of cumulative Es before the rate of soil water supply at the surface decreases below atmospheric demand. The rate of Es during the second stage is specified by the parameter cona as a function of the square root of time (t) since the end of first stage evaporation as follows:

$$\mathrm{Es} = \mathrm{cona} \times t^{1/2}.$$

The value of cona depends on soil hydraulic properties and potential evapotranspiration (ETo) (Prihar et al., 1996; Ritchie, 1972). Potential evapotranspiration is calculated daily using an equilibrium evaporation concept as modified by Priestley and Taylor (1972).

The APSIM SURFACE ORGANIC MATTER module (formerly APSIM-RESIDUE) was developed by Probert et al. (1995, 1998) and is described in detail by Thorburn et al. (2001). The effect of crop residues on runoff is accounted for by modifying the USDA curve number using the relationships from Glanville et al. (1984) which demonstrated that curve number decreases by one unit for every 4% of crop residue cover up to a maximum of 80% cover. The effect of crop residues on the potential drying rate of soil water is also calculated, based on the results of (Adams et al., 1976). SOILN2 is based on the CERES model (Ritchie et al., 1985), with modifications (Probert et al., 1995, 1998). Mineral N is considered as NO_3^-, NH_4^+ and urea. The transformation processes of mineralization, immobilization, denitrification and urea hydrolysis are all simulated in SOILN2.

2.2. Data sets for model calibration and evaluation

2.2.1. Data for model inputs

Replicated field experiments comparing wheat direct-drilled into rice residues and bare soil were conducted on a clay loam soil in Punjab, India, in 2006–2007 and 2007–2008. There were two mulching treatments (with and without mulch) and six irrigation scheduling treatments:

- I_1—irrigation applied when soil water tension increased to 50 kPa at 15–20 cm soil depth for the first irrigation, and at 35–40 cm for subsequent irrigations;
- I_2 (control)—irrigation around the time of crown root initiation (36 d after sowing (DAS) in 2006, 27 DAS in 2007) and thereafter when the ratio of the amount of irrigation water (IW) applied at the previous irrigation to cumulative pan evaporation minus rain (CPE-rain) increased to 0.9, i.e. IW/(CPE-rain) = 0.9 (recommended practice, Prihar et al., 1974);
- I_3—same as I_2 minus the irrigation at crown root initiation (CRI);
- I_4—one irrigation at CRI then irrigation when IW/(CPE-rain) = 0.6;
- I_5—one irrigation only, at CRI;
- I_6—as for I_2 minus the last irrigation.

Seventy-five (75) mm of water were applied at each irrigation for all treatments, therefore IW/(CPE-rain) ratios of 0.9 and 0.6 are equivalent to net CPE of 83 and 125 mm, respectively, between irrigations. Soil water tension in I_1 was measured using tube tensiometers and a SoilSpec® vacuum gauge. The tensiometers were installed mid-way between the plant rows with the tips at 15–20 and 35–40 cm. In 2006–2007, irrigation was applied 36 DAS to all treatments, and because of the well-distributed rainfall, there was no further irrigation of any treatment except for the non-mulched treatment with irrigations scheduled by tensiometer (I_1) which received one irrigation 76 DAS. Therefore only two irrigation treatments could be implemented in 2006–2007—I_1 and I_2. However, in 2007–2008, rainfall was low and poorly distributed and all six treatments were implemented; each irrigation treatment was different