Soil & Tillage Research 100 (2008) 15–24

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Effects of tillage and traffic on crop production in dryland farming systems: I. Evaluation of PERFECT soil-crop simulation model

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ARTICLE INFO

Article history:
Received 4 July 2007
Received in revised form 13 March 2008
Accepted 7 April 2008

Keywords:
Simulation modeling
Curve number
Saturated hydraulic conductivity
Conservation tillage
Controlled traffic
Stubble mulch
Zero tillage

ABSTRACT

Agricultural production systems are complex involving variability in climate, soil, crop, tillage management and interactions between these components. The traditional experimental approach has played an important role in studying crop production systems, but isolation of these factors in experimental studies is difficult and time consuming. Computer simulation models are useful in exploring these interactions and provide a valuable tool to test and further our understanding of the behavior of soil–crop systems without repeating experimentation.

Productivity erosion and runoff functions to evaluate conservation techniques (PERFECT) is one of the soil–crop models that integrate the dynamics of soil, tillage and crop processes at a daily resolution. This study had two major objectives. The first was to calibrate the use of the PERFECT soil–crop simulation model to simulate soil and crop responses to changes of traffic and tillage management. The second was to explore the interactions between traffic, tillage, soil and crop, and provide insight to the long-term effects of improved soil management and crop rotation options. This contribution covers only the first objective, and the second will be covered in a subsequent contribution.

Data were obtained from field experiments on a vertisol in Southeast Queensland, Australia which had controlled traffic and tillage treatments for the previous 5 years. Input data for the simulation model included daily weather, runoff, plant available water capacity, and soil hydraulic properties, cropping systems, and traffic and tillage management. After model calibration, predicted and measured total runoffs for the 5-year period were similar. Values of root mean square error (RMSE) for daily runoff ranged from 5.7 to 9.2 mm, which were similar to those reported in literature. The model explained 75–95% of variations of daily, monthly and annual runoff, 70–84% of the variation in total available soil water, and 85% of the variation in yield. The results showed that the PERFECT daily soil–crop simulation model could be used to generate meaningful predictions of the interactions between crop, soil and water under different tillage and traffic systems.

Ranking of management systems in order of decreasing merit for runoff, available soil water and crop yield was (1) controlled traffic zero tillage, (2) controlled traffic stubble mulch, (3) wheeled zero tillage, and (4) wheeled stubble mulch.

1. Introduction

In recent years, controlled traffic has been widely adopted by dryland farmers in Australia as a strategy for reducing soil compaction and reducing input costs. Controlled traffic with zero tillage provides better protection for both surface and subsurface soil, reducing runoff and improving crop production (Tullberg et al., 2001; Li et al., 2007). In spite of its potential importance, there have still been a few attempts at a broader exploration of traffic and tillage effects in terms of water balance and crop yield effects.

Soil, crop, tillage, wheel traffic and other environmental factors interact with each other and influence both crop performance and water regimes including runoff and soil water status (Tullberg et al., 2001; Li, 2001). These factors, particularly those that are

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doi:10.1016/j.still.2008.04.004

weather related, are often difficult to isolate in experimental studies. An effective computer simulation model might be used to further investigate these factors and explore some interactions between traffic and tillage in cropping systems. Productivity erosion and runoff functions to evaluate conservation techniques (PERFECT, Littleboy et al., 1989, 1999) is one of the soil–crop models that integrates the dynamics of soil and crop processes. Unlike earlier simulation models such as CREAM (Knisel, 1980) and EPIC (Williams et al., 1984), PERFECT was designed to predict runoff, erosion and crop yield for some major management options, including sequences of planting, harvesting and residue management under different tillage practices. This model has been widely used in the dryland farming areas of Australia (Littleboy et al., 1992a,b; Thomas et al., 1995), and in other countries such as China (Wang et al., 2003) and India (Littleboy et al., 1996a,b). A residue cover-infiltration algorithm, derived under simulated rainfall developed by Glanville et al. (1984) and Littleboy et al. (1996b), has been incorporated into PERFECT, together with the effect of tillage induced soil surface roughness (Littleboy et al., 1996a). It appears to be an appropriate and well-tested model for the prediction of infiltration, runoff and crop performance outcomes of soil, crop and fallow management systems.

The objectives of the work reported here were to calibrate PERFECT for four tillage and traffic management practices, using daily weather, runoff, soil water and crop yield data obtained from experimental plots. USDA curve number was used in the water balance sub-model (Rallison and Miller, 1982). Changes in USDA curve number of bare soil at average soil water content (CN_{II}) and the saturated hydraulic conductivity (K_{sat}) of the soil horizon were explored to determine the ability to explain effects of these management options on variations in measured runoff by use the PERFECT model.

2. Curve number and K_{sat}

Curve number is one of the major factors used, largely for runoff prediction, in the water balance sub-model of PERFECT. The curve number function is empirically derived from fitting measured runoff data and the physical process of infiltration is not represented (Boughton, 1989). The curve number approach does not require detailed information on soil properties, rainfall intensity or energy (Connolly, 1998). Previous experience with the USDA curve number method in Australia used antecedent rainfall as a surrogate for antecedent soil moisture. Silburn and Freebairn (1992) reviewed a number of studies in Australia and concluded that the use of antecedent rainfall is a major limitation to the use of curve number method, and developed an improved curve number procedure using a continuous soil water function to achieve a better performance than previous methods.

Despite its simplicity, quite good predictions of cumulative runoff are possible with models using the optimized curve number procedure. The curve number effectively combines the effects of soil hydraulic conductivity, soil surface crusting and microtopography on runoff, and a saturated hydraulic conductivity parameter is usually applied to control the rate of infiltration and drainage. Infiltration via cracks and macropores, an important factor in shrinking and cracking soil, is simply represented as by-pass flow in the PERFECT model.

The effects of soil management factors such as crop residues and tillage system on runoff have been incorporated into PERFECT (Littleboy et al., 1989, 1999). The relationship between surface cover and curve number was defined by Glanville et al. (1984) in Queensland and by Littleboy et al. (1996b) in India. Both Littleboy et al. (1992a,b) and Silburn and Freebairn (1992) reported that runoff prediction was improved when this relationship was included in the curve number procedure.

Most tillage and cropping systems entail random field traffic, and previous modeling research has not specifically addressed this, or the possibility of controlling traffic and its interaction with tillage and cropping systems. The increased adoption of controlled traffic systems in Australia underlines the need to study and understand its long-term effects. The PERFECT model is a candidate for such a study because it incorporates a continuous function of soil water, conservation tillage and residue surface cover effects and fallow management.

Previous model calibration has been performed by optimizing CN_{II} to minimize the differences between measured and predicted data (Silburn and Freebairn, 1992). CN_{II} is the curve number for bare soil at average antecedent moisture content with a continuous function of soil water, and is one major parameter required in the curve number procedure. Saturated hydraulic conductivity (K_{sat}) for each layer has usually been obtained from published data and held constant during model calibration (Silburn and Freebairn, 1992; Littleboy et al., 1992a,b; Thomas et al., 1995). No reports were found in the literature on model calibration by optimizing K_{sat}. In this study, the PERFECT was calibrated by optimizing both CN_{II} and K_{sat}.

3. Description of experimental site

The PERFECT model was evaluated using data collected from 1995 to 1999 on a controlled traffic experiment at the University of Queensland, Gatton, Australia (27°34′ S, 152°20′ E). The experimental site was a black vertisol (sometimes spelled vertosol), an adhesive shrink–swelling clay soil as classified by Isbell (2002). This comprised a 0.6–1.0 m surface layer of black earth, exhibiting typical self-mulching characteristics and moderate cracking, overlaying a highly permeable gravel and sand mixture. Four blocks were laid out diagonally across the slope to provide a mean slope of 6–8% (α) and ensure that all runoff water from any one plot would drain into the traffic lane or furrow defining its lower boundary. The experiment consisted of four 24 m-wide blocks, with each block comprising six plots with one guard row at each side. Each of the 24 plots was equipped with instrumentation for runoff monitoring. A bed length of 30 m was chosen to provide a runoff collection area of 90 m^2 within the available slope length.

A split-plot experimental design was used with two traffic treatments—controlled traffic (C, non-wheeled seedbed) and wheeled (W, wheeled seedbed) within each tillage treatment. Three tillage treatments (zero tillage: ZT, stubble mulch: SM and minimum tillage: MT) were initiated in 1995. The minimum tillage results were always between those of the zero tillage and stubble mulch (Tullberg et al., 2001) so this treatment was discontinued after 1998 leaving only ZT and SM treatments.

Two wheel traffic treatments, wheeled and controlled traffic, where applied to each of the two tillage treatments resulting in four treatments: controlled traffic zero till (CZT), controlled traffic stubble mulch (CSM), wheeled zero till (WZT) and wheeled stubble mulch (WSM). Stubble mulch plots normally received three passes of a heavy-duty spring tine chisel plow between summer and winter crops. The first pass was at a depth of approximately 125 mm, with shallower depths for subsequent passes. Zero till plots normally received no tillage treatment prior to planting. The planter was not able to penetrate heavy crop residues so residue was sometimes removed before planting and manually replaced afterward on the zero till plots.

All treatments were managed using a tractor of 3 m trackwidth, so the 2.5 m wide crop zone was driven over by wheels only as a deliberate treatment. The entire plot area of wheeled treatments received a single wheeling from three adjacent lengthways passes with a front wheel assist tractor so that the wheel tracks covered the complete 2.5 m crop zone. The tractor had a static rear axle weight of 40–50 kN, and was fitted with single 18.4 or 20.4 in section tyres (respectively 467 and 518 mm width) inflated to approximately 100 kPa. The wheeling treatment was applied annually and immediately before the primary tillage operation preceding winter wheat planting. The wheeling treatment on the small plots was intended to simulate the effect of random wheel traffic for normal field operations, while no wheels were allowed on the controlled traffic plots. A detailed description of the experimental site, treatments, and data collection procedure is given in Tullberg et al. (2001) and Li et al. (2001).

4. Model input and parameter values

4.1. Weather and runoff data

On-site rainfall and runoff were measured at 1.0 min intervals and accumulated into daily totals to provide a daily rainfall and runoff record for the PERFECT model calibration (Tullberg et al., 2001; Li et al., 2007). There were four pluviometers at the experimental site, so the most reliable was selected to provide most daily rainfall values and the other three were used as backups in the case of missing data. Daily temperature, radiation and evaporation data were supplied by the meteorological station (station number: 040082) at The University of Queensland Gatton, located approximately 1.0 km from the experimental site. Average monthly rainfall and pan evaporation during the experiment are illustrated in Fig. 1.

4.2. Soil parameters

Measured values of soil physical properties were used as inputs to the PERFECT model to minimize problems that can occur when calibrating a large number of interrelated parameters (Littleboy et al., 1996a). Soil water content was monitored throughout the cropping and fallow periods using two access tubes per plot for soil moisture measurement with a neutron probe unit (CPN Model 503 Nuclear Moisture Meter, CPN International Inc., Concord, U.S.A). This unit was calibrated at each depth interval for each treatment over a wide range of soil water content. The plant available water capacity (PAWC) of the soil was determined by taking the difference between the wettest and driest soil water measurements for each treatment at eight depths, 200, 300, 400, 500, 600, 800, 1000 and 1200 mm, and integrating over the total depth. The upper and lower limits of plant available water at each measurement depth were assumed to be equal to the respective wettest and driest soil water measurements (Littleboy et al., 1996a).

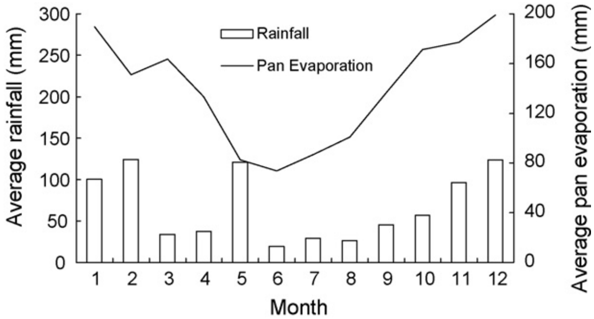

Fig. 1. Average monthly rainfall and pan evaporation during the field experiments from 1995 to 1999.

Soil water content at saturation (SAT) was inferred from measured bulk density (BD) using the relationship given in Eq. (1) where SAT was the saturation water content and BD is the bulk density (g/cm^3) at each measurement depth, and 2.65 is the assumed particle density (g/cm^3) (Littleboy et al., 1996a). Air-filled porosity of 0.05 v/v at the upper limit was assumed to be generally valid for swelling clays (Gardner, 1988).

$$SAT = 0.95\left(1.0 - \frac{BD}{2.65}\right) \quad (1)$$

Soil evaporation parameters CONA (slope of stage II soil evaporation curve) and U (upper limit of stage I soil evaporation, mm) were set to constant values of 3.75 and 8.25 mm, respectively, as suggested by Ritchie (1972) for clay soils. Air-dry soil water content for all treatments was taken from published data (Powell, 1982).

The relationships between curve number and residue cover under controlled traffic and wheeled conditions were obtained from rainfall simulation experiments (Li et al., 2001). CN_{II} for CZT was 78 and the maximum reduction due to residue cover was 23. CN_{II} for soil wheeled with 10% wheelslip was 92, and the maximum reduction due to residue cover was three. The values of curve number reduction due to tillage were not available for a vertisol in Australia; therefore, the values obtained from the results of Littleboy et al. (1996a) on an Alfisol in semi-arid tropical India were used in this study. Rainfall after tillage was used as an index of energy to remove tillage roughness effects (Freebairn et al., 1989).

Saturated hydraulic conductivity (K_{sat}) is normally obtained from published data for both upper (0–100 mm) and lower layers (100–1000 mm) (Littleboy et al., 1992b; Silburn and Freebairn, 1992). In this study, K_{sat} for both upper and lower layers was derived from field experimental data. Soil parameter data derivations are summarized in Table 1.

4.3. Crop and tillage management parameters

The cropping program was similar to that normally used by dryland farmers in Southeast Queensland, Australia, although supplementary irrigation was provided on several occasions to create a planting opportunity and maximize the number of crops in the data set. No fertilizer was applied in the first 3 years of this work to encourage crop root systems to exploit soil resources to the maximum extent. Crop rotations include wheat and sorghum, maize, sunflower and sweet corn. Crop and tillage management information, including crop variety, planting dates and population, dates and types of tillage operations were recorded throughout the field experiment. There was no sweet corn module in the PERFECT model, so standard maize parameters were used instead parameters specific to sweet corn.

Table 1
Summary of soil parameter derivation

Parameter	Method
CN_{II}	Measured/calibrated
K_{sat} (0–100 mm)	Calibrated
K_{sat} (100–1000 mm)	Calibrated
Air dry water	Published data (Powell, 1982)
Drained upper limit/lower limit	Measured data
CONA/U	Published data (Ritchie, 1972)
Saturation moisture content	Calculated
CN reduction: due to residue cover under controlled traffic and wheeled	Derived from rainfall simulator
CN reduction: due to tillage	Published data (Littleboy et al., 1996a)

4.4. Model calibration runs

Model calibration is a technique where model parameters are systematically adjusted to minimize the differences between measured and simulated values. The values of CN_{II} and K_{sat} for upper and lower soil layers were determined by fitting the model to measured runoff, soil water and crop yield data. Various combinations of the two parameters may give similar predicted runoff and soil water, so the procedure outlined below was developed to fit the parameters as independently as possible. The crop growth sub-model was first adjusted to fit crop performance (yield, harvest date, etc.) by altering degree–days and radiation use efficiency (Littleboy et al., 1999).

The criteria for optimization of runoff and soil water prediction were the minimization of root mean square errors (RMSE) between measured and predicted data. The model calibration procedure to determine optimum CN_{II} and K_{sat} followed four steps. These are detailed below:

(1) Rainfall simulation experiments (Li et al., 2001) were used to provide values of bare soil CN_{II} under CZT. K_{sat} for both the upper and lower layers were systematically varied over the normal range for the similar soils. The lowest values of the RMSE occurred when K_{sat} for both the upper and lower layers was approximately the same under CZT. This was not unexpected because these plots had not been subject to wheel traffic or tillage for 5 years (and eight crops) prior to the start this experiment, during which time natural amelioration would have generated a more uniform profile.
(2) The same amelioration would have occurred in the lower layer of CSM and CZT plots, so, K_{sat} (of the lower layer) should be equal for both treatments. The value of the K_{sat} of the lower layer derived from the CZT optimization was used as input for the CSM treatment. CN_{II} and K_{sat} of the upper layer were unknown parameters and were determined by fitting the model to measure runoff, soil water and crop yields. The optimum values of CN_{II} for minimum RMSE were slightly different for each runoff, soil water and crop yield, so a compromise value of CN_{II} was selected which produced an RMSE value very close to the minimum for runoff, soil water and crop yield.
(3) A similar approach (to that for CZT) was adopted to optimize K_{sat} for both upper and lower layers of WZT. CN_{II} was measured during rainfall simulation experiments (Li et al., 2001) and K_{sat} was obtained by fitting the model to measured data, but in this case, the K_{sat} value of the upper layer should be the same as that for the upper layer of CTZ.
(4) Both the WSM and WZT had received similar wheeling treatments, so K_{sat} of the lower layer of these two treatments should be equal. A procedure similar to step 2 was used to obtain CN_{II} and K_{sat} for upper layer by fitting the model to measured data.

5. Results of model calibration

5.1. Optimization of CN_{II} and K_{sat} values

Optimized values of CN_{II} and K_{sat} for different layers, together with statistics of fit with daily runoff are given in Table 2.

The number of events during the 5-year experimental period which produced runoff was 22% greater for the wheeled treatments than for the controlled traffic treatments. The ranking of the four treatments in order of increasing CN_{II} was CZT (78), CSM (89), WZT (92) and WSM (93) (Table 2). K_{sat} of the lower layer under controlled traffic was four times higher than under wheeled practices. Compared with zero tillage practice, K_{sat} of the upper layer was reduced by about 20% for stubble mulch due to the reduction of surface residue cover under tillage (Table 2).

5.2. Daily runoff and curve number prediction

The predicted total runoff for the 5-year period was similar to the measured total runoff for all four treatments with values of RMSE for daily runoff ranging from 5.7 to 9.2 mm (Table 2). Measured and predicted daily runoff volumes for the four treatments are shown in Fig. 2. The model explained 75–89% of the variation in daily runoff volumes. For wheeled treatments, there was no evidence of the model consistently over-predicting or under-predicting daily runoff volume; the deviations between predicted and measured runoff were evenly distributed on either side of the 1:1 line throughout the range of measured runoff values (Fig. 2c and d). In the case of the controlled traffic treatments, however, runoff values were substantially over-predicted on a number of occasions (Fig. 2a and b). These were the extreme events in early May 1996 when 429 mm of rain fell within a 6-day period.

Daily curve number under different traffic and tillage treatments was predicted, and the effect of tillage, residue and crop cover was taken into account in the PERFECT model. For the two controlled traffic treatments (Fig. 3), curve number ranged between 55 and 90, and was significantly affected by soil surface cover by crop residue and growing crop. For example, in early 1998, curve number was 56 and 87 CZT and CSM, respectively. For CZT, the curve number increased with the small decrease in residue cover following planting and then decreased slightly as the

Table 2
Results for prediction of total runoff calibrated using the PERFECT model with optimized CN_{II} and K_{sat} values

Treatment	n	Curve number (CN_{II})	K_{sat} (mm/h)		O:P total runoff	RMSE (mm)	R^2
			UL	LL			
CZT	113	78[a]	1.01[b]	1.01[b]	1.00	9.2	0.75
CSM	119	89[b]	0.80[b]	1.01[a]	1.00	7.1	0.85
WZT	139	92[a]	1.01[a]	0.25[b]	0.96	5.9	0.87
WSM	143	93[b]	0.80[b]	0.25[a]	0.96	5.7	0.89
All data combined							
Daily	514				0.99	7.0	0.82
Monthly	240				0.97	16.2	0.87
Annual	20				0.97	57.5	0.80

n: number of observations; CN_{II}: USDA curve number for bare soil and average antecedent soil moisture; UL: upper layer soil (1–100 mm); LL: lower layer soil (100–1000 mm); RMSE: root mean square error (mm); O:P total runoff: ratio of total observed and total predicted runoff.

[a] Known parameters in model calibration run.

[b] Unknown parameters in model calibration run.

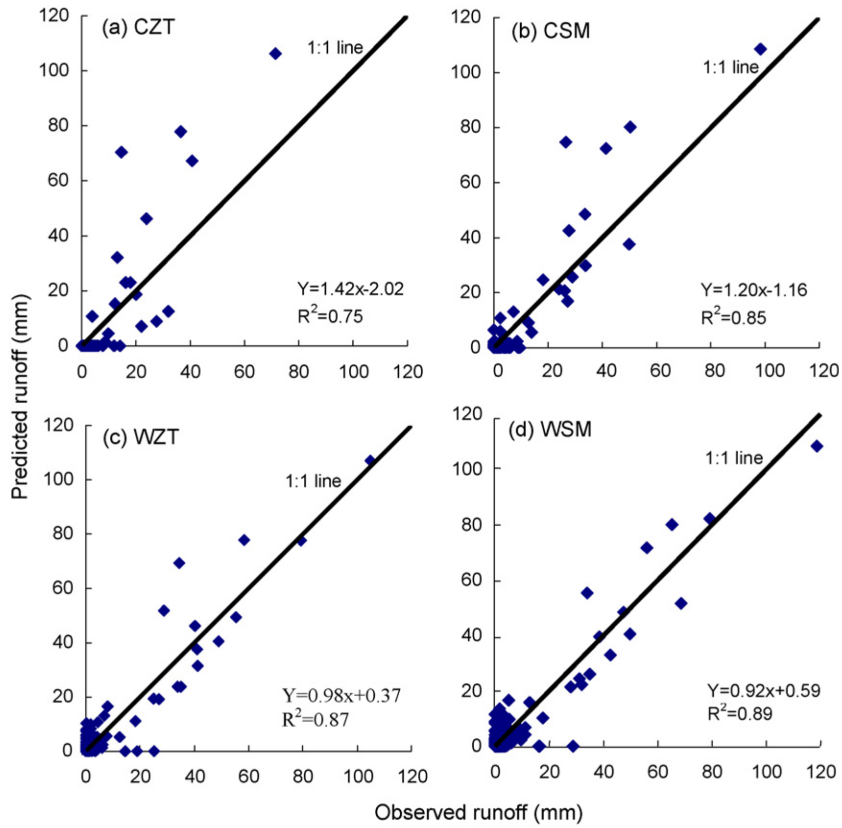

Fig. 2. Predicted and observed daily runoff volumes for four traffic and tillage management practices from 1995 to 1999.

crop grew and residue decayed. For CSM with less residue cover, the curve number increased to 90 in the first 2 months with no crop, decreased slightly with increased soil roughness from tillage prior to planting, increased immediately after planting, and then decreased to 80 as the crop grew and provided cover for the soil. Similar trends were observed in 1999 when there were two crops in that year. The average daily curve number was 61 for CZT and 80 for CSM over 5 years.

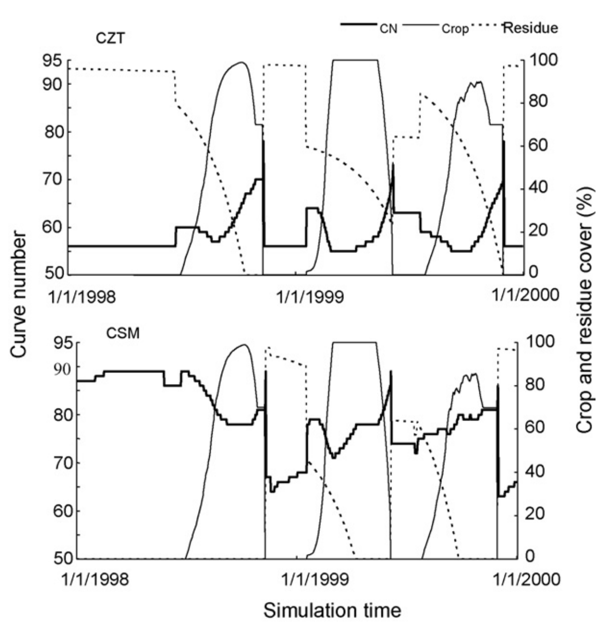

Fig. 3. Effect of crop and residue covers on curve number for CZT and CSM practices from 1 January 1998 to 2000. Three crops during these 2 years, two crops for winter wheat seeded in middle of 1998 and 1999 and harvested at the end of 1998 and 1999, respectively; one crop for sweet corn seeded in early 1999 and harvested in middle of 1999 prior to wheat seeding. There was no tillage operation under zero till, but tillage operation occurred prior to seeding each crop under stubble mulch.

For wheeled treatments (Fig. 4), curve number ranged between 87 and 93, and was significantly affected by soil compaction compared with controlled traffic treatments. Crop and residue cover had less effect on curve number compared with controlled traffic treatments. The average daily curve number was 90 for WZT and 92 for WSM over 5 years.

5.3. Monthly and annual runoff prediction

Comparison of predicted and observed monthly runoff for all four treatments is presented in Fig. 5. The model provided good predictions for monthly runoff for all treatments except for controlled traffic zero tillage, in which runoff was over-predicted by 50% for the extreme events of May, 1996 (Fig. 5a). All R^2 values were greater than 0.90, except for controlled traffic zero tillage.

The prediction statistics for the combined runoff data are presented in Table 2. As with daily runoff predictions, the model gave better monthly runoff prediction for wheeled than non-wheeled treatments (Fig. 5). The large over-prediction for controlled traffic corresponded to the extreme event in May 2006 (Fig. 5a and b). Annual runoff predictions for all four treatments are compared with observed runoff in Fig. 6.

5.4. Prediction of total available soil water

Prediction statistics of total available soil water in the profile (1.0 m) for the four treatments are shown in Table 3. Values of RMSE were similar for all treatments, ranging from 26.5 to 29.4 mm with mean errors between −14.4 and +12.2 mm for the

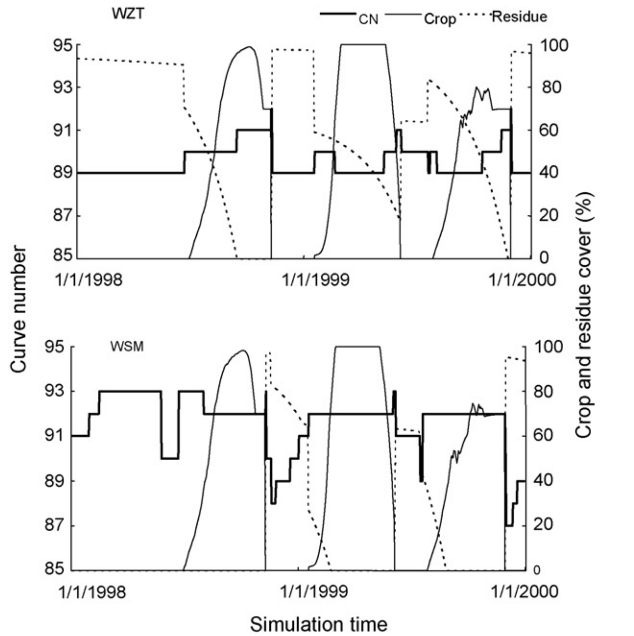

Fig. 4. Effect of crop and residue covers on curve number for WZT and WSM practices from 1 January 1998 to 2000. Three crops during these 2 years, two crops for winter wheat seeded in middle of 1998 and 1999 and harvested at the end of 1998 and 1999, respectively; one crop for sweet corn seeded in early 1999 and harvested in middle of 1999 prior to wheat seeding. There was no tillage operation under zero till, but tillage operation occurred prior to seeding each crop under stubble mulch.

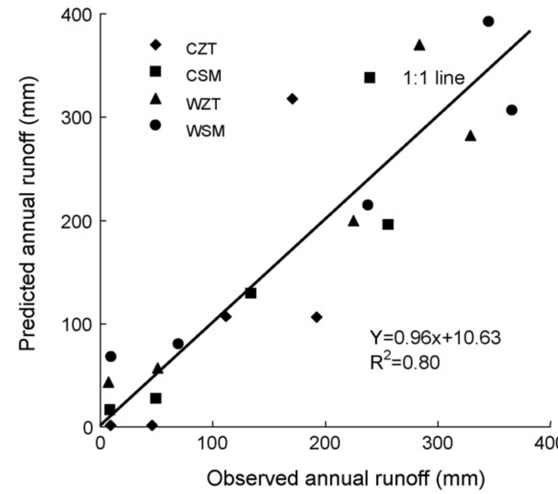

Fig. 6. Predicted and observed annual runoff (n = 20) for four management practices from 1995 to 1999.

WSM and CZT treatments, respectively. Slopes for regression of predicted against observed soil water ranged from 0.79 to 0.89 with R^2 from 0.78 to 0.84. Comparison of observed and predicted total available soil water is presented in Fig. 7. In general, the model gave slightly better R^2 for zero till than for stubble mulch. The model explained 78–84% of the variation in total available soil water.

The temporal trend of total available soil water is shown in Fig. 8, based on 44 observations during four summer cropping

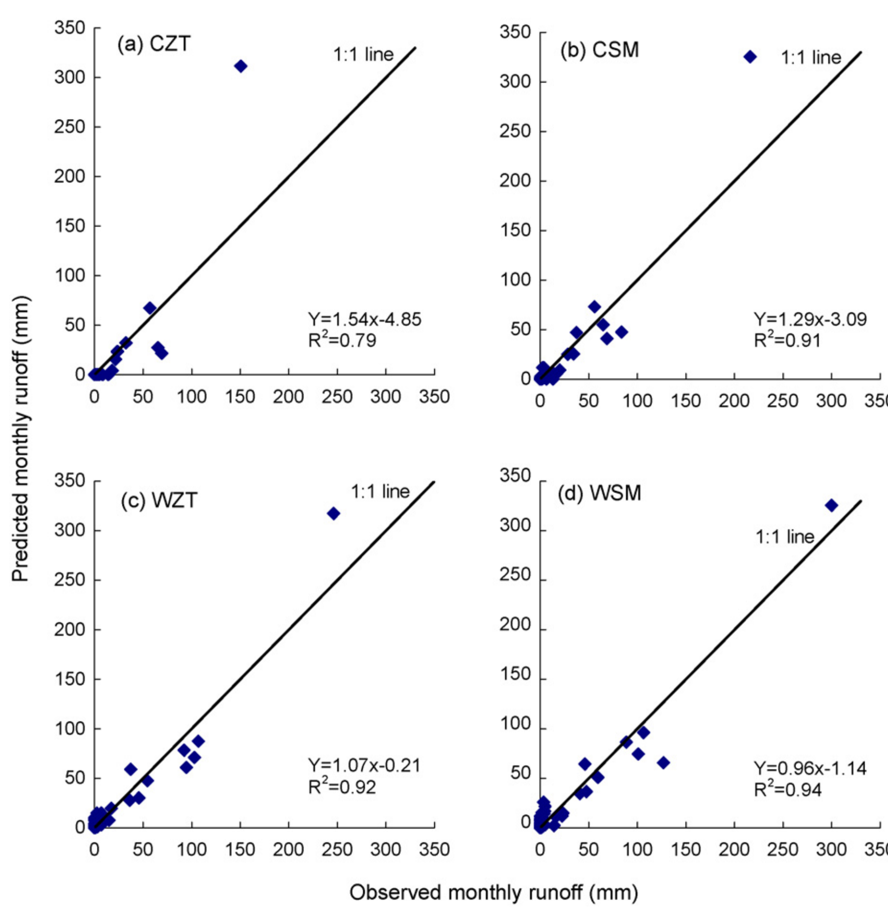

Fig. 5. Predicted and observed monthly runoff for four management practices from 1995 to 1999.

Table 3
Results for prediction of available soil water for 1.0 m soil profile calibrated using PERFECT model

Treatment	n	RMSE (mm)	Mean error (mm)	Int. (mm)	Regression slope	R^2
CZT	44	26.5	12.2	33.1	0.80	0.84
CSM	44	26.5	−8.6	13.5	0.79	0.78
WZT	44	27.4	−12.6	2.0	0.86	0.80
WSM	44	29.4	−14.4	−3.6	0.89	0.78

n: number of observations; RMSE: root mean square error; liner regression: predicted = slope × (observed) +Int. for available soil moisture values.

Table 4
Observed and predicted average yields (kg/ha) of winter and summer crops from 1995 to 1999 for four management practices

Treatment	Winter wheat		Summer crops	
	Observed	Predicted	Observed	Predicted
CZT	2826	2715	6495	5291
CSM	2747	2481	6355	5246
WZT	2618	2318	6175	5073
WSM	2574	2171	5775	4925

periods in 1995 and 1999, and winter wheat in 1997 and 1998. Model predictions and observations were similar in 1998 and 1999 for CZT, but over-prediction occurred in 1995 and 1997. Total available soil water was well predicted in all years except 1999 when it under-predicted by up to 50 mm soil water (25%) for all treatments except controlled traffic zero tillage.

5.5. Crop yield prediction

Observed and predicted grain yield for the four treatments is shown in Fig. 9. The model explained 85% of the variation in mean grain yield, but consistently under-predicted mean yield. It under-predicted yield by 4–16% and 15–19% for winter and summer crops, respectively, depending on treatment (Table 4). The model gave better prediction of winter wheat yield for CZT with only 4% under-prediction. The ranking of treatments in order of decreasing predicted yield was controlled traffic zero tillage, controlled traffic stubble mulch, WZT and WSM. The ranking was the same for predicted and experimental yield (Table 4).

6. Discussion

6.1. CN_{II} and K_{sat} calibrations

This study used both CN_{II} and K_{sat} approach to identify which soil profile layers were controlling infiltration, using the PERFECT simulation model. For controlled traffic, surface conditions such as roughness due to tillage and cover from either crop or residue had a greater effect on runoff and infiltration. Saturated hydraulic conductivity (K_{sat}) below 100 mm for controlled traffic soil was four times greater than that for wheeled soil, indicating that subsurface compaction was a major impact affecting infiltration

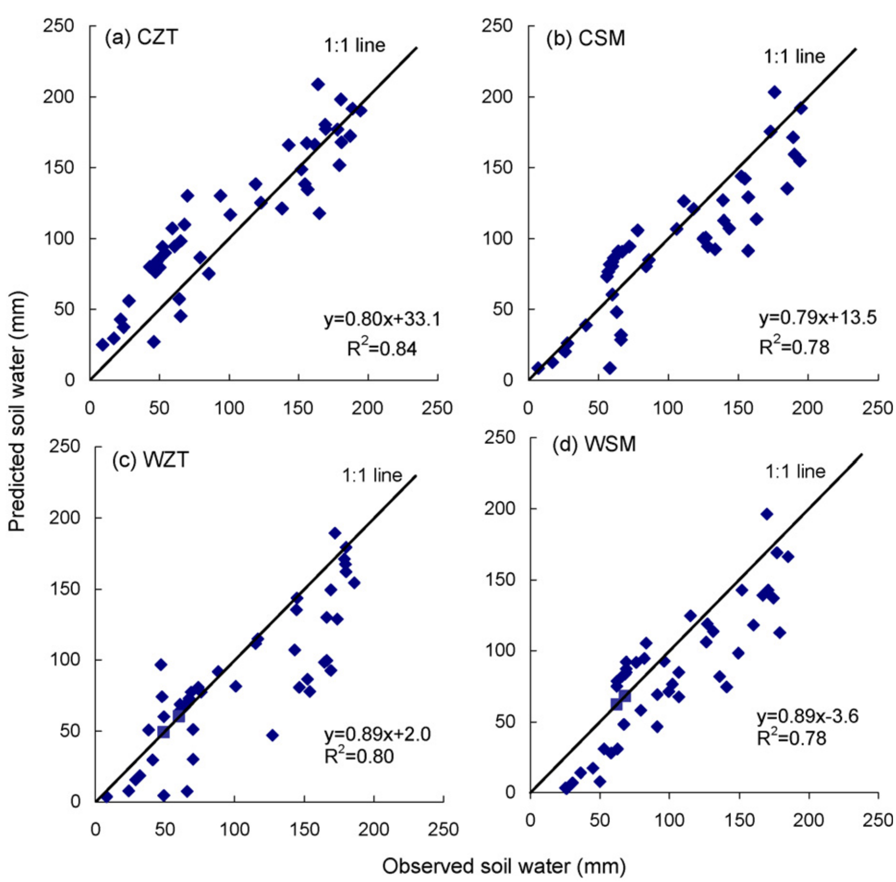

Fig. 7. Predicted and observed daily available soil water volumes for four traffic and tillage management practices from 1995 to 1999. Soil profile was 1 m in depth.

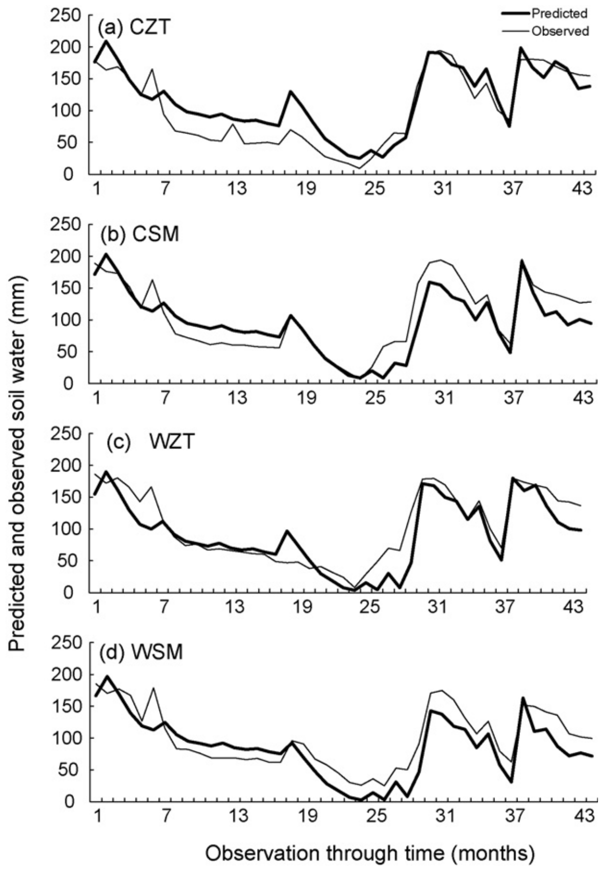

Fig. 8. Temporal trend of measured and predicted daily available soil water through time for four traffic and tillage management practices from 1995 to 1999. Soil profile was 1 m in depth.

and water redistribution under wheeled conditions. For WSM soil, reduced hydraulic conductivity in both the upper layer (tillage effect) and lower layer (traffic effect) resulted in less infiltration and more runoff. Stubble mulch reduced the saturated hydraulic conductivity of the surface layer by 20% compared with zero tillage.

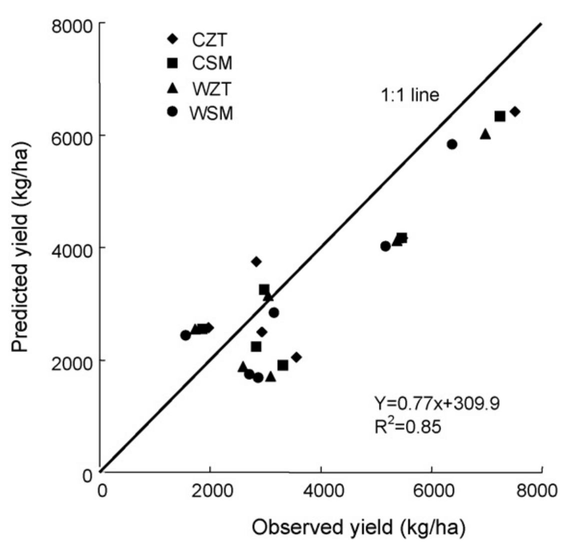

Fig. 9. Predicted and observed crop yield for four traffic and tillage management practices from 1995 to 1999 ($n = 24$, $P < 0.05$).

McHugh et al. (1999) used disc permeameters to measure saturated hydraulic conductivity over a 4-year period in a similar soil at a nearby site. They found that saturated hydraulic conductivity of non-wheeled zero tillage soil in 100–300 mm layer was 3.5 times greater than that of annually wheeled soil. A single tractor wheel treatment of side-by-side passes with a tractor wheel roughly halved hydraulic conductivity of controlled traffic soil at this site. Connolly (2000) found that K_{sat} was reduced by 80% after 30 years of cropping compared to a virgin soil. Boone (1988) also reported significant soil compaction-induced reductions in K_{sat}. These data are in agreement with our K_{sat} estimates derived in model calibration.

Values of CN_{II} for bare soil were 92 and 93 for WZT and WSM practices, respectively. These are consistent with the results of Littleboy et al. (1996a), who reported CN_{II} of 94 for bare soil at average soil water content under a random traffic system on an Alfisol in sub-tropical India, using the same model. Silburn and Freebairn (1992) using the CREAMS model, which does not account for residue and tillage effects, reported curve numbers of 61, 69 and 71 on a black earth (Australian vertisols) for stubble mulch, zero tillage and bare fallow, respectively, after 5–8 years of random traffic.

Mean curve numbers over 5 years were 61, 80, 90 and 92 for CZT, CSM, WZT and WSM, respectively and the data suggests that traffic, tillage and cover effects are cumulative. The lowest curve number occurred under CZT soil, while the highest curve number occurred under WSM soil. These two treatments represent the extremes of traffic and residue cover. Controlled traffic zero till has the least (zero) traffic and greatest residue while WSM has the greatest traffic and least residue cover. As expected, both traffic and residue cover affects the curve number. The maximum difference in curve number due to the effects of traffic, tillage and residue cover was 31.

6.2. Runoff prediction

The experimental data illustrate large differences in runoff as a consequent of different combinations of traffic, tillage and residue management. Measured average annual runoff ranged from 100 to 200 mm for all treatments. This large variation in runoff was successfully simulated using the PERFECT model. The RMSE range of 5.7–9.2 mm was similar to the 3.0–9.0 mm range reported by Littleboy et al. (1992c) for a sub-tropical Australian soil, and 3.0–7.0 mm for an Alfisol soil in India reported by Littleboy et al. (1996a) using the PERFECT model. Silburn and Freebairn (1992) reported an RMSE range of 7.3–9.7 mm for similar soil in Queensland using the CREAMS model.

The PERFECT model explained 75–94% of variation in daily runoff volumes due to traffic and tillage and associated surface cover without further calibration. It gave better predictions of monthly and annual runoff than of daily runoff. This was expected as the errors in soil water status over short time periods predicted by the model tend to average out over longer time periods.

The poor runoff predictions for controlled traffic treatments are not surprising because models such as PERFECT have been developed and calibrated for use in normal farming conditions. In conventional farming, random wheel traffic impacts 50–100% of land area in every crop production cycle, whereas controlled traffic comprises 85% non-trafficked crop zone with very different characteristics to the 15% of severely trafficked permanent lanes. Another reason for the poor prediction might be the smaller number of events which resulted in runoff from controlled traffic treatments. A similar effect was found by Littleboy et al. (1992c), in which RMSE was the highest for zero tillage compared with many other treatments.

6.3. Prediction of total available soil water and crop yield

The model gave a reasonable prediction of total available soil water, and the RMSE values of 26–36 mm were similar to those reported by Littleboy et al. (1992a) and Silburn and Freebairn (1992). Predicted maximum available soil water of about 200 mm was in good agreement with measured values for this soil (Littleboy et al., 1992a; Silburn and Freebairn, 1992). Functional representation of soil water indicated that the detailed representation of the soil in the PERFECT model was effectively parameterized.

Prediction of crop yield in PERFECT was low, but still relatively accurate when compared with other studies; Connolly (2000), using improved PERFECT-SWIM, reported a R^2 of 0.54 for wheat yield and Littleboy et al. (1992b) using PERFECT, reported R^2 of 0.75 for winter and summer crops. The model also correctly predicted the trends of the effect of traffic and tillage management on average yield over the 5-year period. However, the model did not include algorithms for other factors such as insects, disease and N mineralization, which affect yield and might vary with traffic and tillage management (Freebairn et al., 1990).

6.4. Limitation and improvement

This model was calibrated with a minimum 5-year dataset in a vertisol in Northeast Australia. Curve numbers and wheeling relationships are site-sensitive, and may change with the environment and soil, so the results may differ if this model is tested under different soil and climatic conditions. This work also took a different approach from previous studies by using an optimized model for estimating K_{sat}. The assumptions involved appear reasonable, and are clearly defined. The acceptable fit between predicted and experimental results supports the validity of this procedure.

7. Conclusion

The PERFECT soil–crop simulation model was calibrated using 5 years of experimental data, and values of CN_{II} established from rainfall simulation tests. Calibration was accomplished by adjusting K_{sat}, and CN_{II}, to explore the capacity of PERFECT to model the effects of combinations of traffic and tillage management. In the calibrated model:

(1) The model explained 75–95% of variations of daily, monthly and annual runoff values. The model over predicted runoff from controlled traffic treatments in extreme rainfall events.
(2) The model explained 81% and 85% of the variation in total plant available soil water content and crop yield, respectively.
(3) Under CZT, with no tillage or traffic applied to the soil, K_{sat} is the same for both upper and lower layers. This indicates that it is possible to estimate K_{sat} by using PERFECT model. Further study is needed to identify the effect of K_{sat} on model prediction.
(4) K_{sat} for lower layers changed with the traffic treatment. In the absence of wheel traffic under controlled traffic, K_{sat} below 100 mm depth was four times greater than that in wheeled soil. K_{sat} for upper layers changed with tillage arrangement. K_{sat} between 0 and 100 mm under stubble mulch was 80% of that with zero tillage.
(5) The maximum difference in mean curve number due to traffic, tillage and residue cover treatments was 31.

Acknowledgements

This work was supported by the Australian Centre for International Agricultural Research (ACIAR), under project numbers 9209 and 96143. We thank Mr. M. Littleboy for his generous assistance in model calibration through all stages and Dr. R. Connolly for his help and advice in modeling. We also thank Mr. B. Jahnke and Mr. G. Groth for technical assistance throughout this work.

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