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Effects of tillage and traffic on crop production in dryland farming systems: II. Long-term simulation of crop production using the PERFECT model

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ABSTRACT

Soil water conservation is critical to long-term crop production in dryland cropping areas in Northeast Australia. Many field studies have shown the benefits of controlled traffic and zero tillage in terms of runoff and soil erosion reduction, soil moisture retention and crop yield improvement. However, there is lack of understanding of the long-term effect of the combination of controlled traffic and zero tillage practices, as compared with other tillage and traffic management practices.

In this study, a modeling approach was used to estimate the long-term effect of tillage, traffic, crop rotation and type, and soil management practices in a heavy clay soil. The PERFECT soil–crop simulation model was calibrated with data from a 5-year field experiment in Northeast Australia in terms of runoff, available soil water and crop yield; the procedure and outcomes of this calibration were given in a previous contribution. Three cropping systems with different tillage and traffic treatments were simulated with the model over a 44-year-period using archived weather data.

Results showed higher runoff, and lower soil moisture and crop production with conventional tillage and accompanying field traffic than with controlled traffic and zero tillage. The effect of traffic is greater than the effect of tillage over the long-term. The best traffic, tillage and crop management system was controlled traffic zero tillage in a high crop intensity rotation, and the worst was conventional traffic and stubble mulch with continuous wheat. Increased water infiltration and reduced runoff under controlled traffic resulted in more available soil water and higher crop yield under opportunity cropping systems.

1. Introduction

The productivity of cropping systems in the short-term is determined predominantly by soil type, weather, disease and insects, and traffic and tillage management. However, long-term production depends on conservation of soil resources (Freebairn and Gupta, 1990; Littleboy et al., 1992b). To prevent soil degradation and optimize crop production, traffic and tillage practices must be managed to suit the climate, crop rotation and soil resources.

A highly variable climate and unreliable water supply is a major constraint to crop production in dryland farming (Freebairn and Boughton, 1981). Better traffic and tillage management can improve sustainable crop productivity by creating favorable soil conditions for rain-water to infiltrate into soil (Li et al., 2001, 2007). Timing of cropping to optimize water use can also be applied to improve productivity and sustainability (Freebairn and Gupta, 1990; Freebairn et al., 1989).

Field experiments to evaluate different management practices must be run over many seasons to obtain reliable results. This is expensive, time consuming and in many cases impractical (Connolly, 2000). During the period of field experiments, dry or wet weather extremes may be present and not reflect long-term conditions (Freebairn and Gupta, 1990), making it difficult to extrapolate short-term results to long-term expectations.

Simulation models can integrate the major physical and biological processes and predict long-term responses (Freebairn and Gupta, 1990). A simulation model can be used as an experimental framework for integrating information from complex agricultural systems, including soil, water, machine, tillage equipment and climate data (Silburn and Freebairn, 1992; Connolly, 1998). It can also be used as a method of applying knowledge from different practices and as a mechanism to predict long-term responses based on short-term experimental data (Littleboy et al., 1992b; Silburn and Freebairn, 1992). Long-term simulation can provide a probabilistic

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analysis of outcomes from a wide range of alternative management practices, thus accelerating our learning about management options (Freebairn and Gupta, 1990).

PERFECT (Productivity Erosion and Runoff Functions to Evaluate Conservation Techniques) (Littleboy et al., 1989, 1999) is one of the soil–crop models that integrate the dynamics of soil and crop processes. This model was designed to predict runoff, erosion and crop yield for some major management options in dryland cropping areas including sequences of planting, harvesting and stubble management. This model has been used in large dryland farming areas in Australia (Littleboy et al., 1992a, 1992b; Thomas et al., 1995), and in other countries such as China (Wang, 2000) and India (Littleboy et al., 1996a, 1996b). A soil cover-infiltration algorithm, derived under simulated rainfall by Glanville et al. (1984) and Littleboy et al. (1996b), and the effect of tillage induced roughness (Littleboy et al., 1996a) have been incorporated into PERFECT. 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. This model was calibrated using 5-year field experimental data in the same site to explore its capacity to model traffic and tillage management (Li et al., in press). The results of the calibration indicated that the model is capable of simulating the impact of soil management on important soil processes, such as infiltration, runoff, soil water and crop yield in a heavy clay soil in Northeast Australia.

The objectives of the work reported in this paper are: (a) to explore the most efficient options to manage traffic and tillage systems, to reduce climate risk, and to improve dryland crop production, and (b) to assess the long-term effects of traffic and tillage on water balance, soil loss and crop yield for continuous wheat, continuous sorghum and wheat–sorghum opportunity cropping systems.

2. Weather and soil data for model simulation

Long-term weather data i.e. daily rainfall, radiation, pan evaporation, maximum and minimum temperature, were available from the meteorological station (Lawes weather station, station number 040082) at the University of Queensland Gatton (27°34′S, 152°20′E). This station was located approximately 1 km from the experimental site. A comparison of daily rainfall between the experimental site and Lawes weather station from 1995 to 1999 is presented in Fig. 1, and average monthly rainfall and pan evaporation over 44 years from 1957 to 2000 is illustrated in Fig. 2.

In addition to weather and soil data, the PERFECT model requires USDA curve number (CN), and saturated soil hydraulic conductivity (Ksat) for each tillage and traffic treatment. The curve number for selected treatments was obtained from independent rainfall simulation field experiments. The model was then calibrated by systematically adjusting these parameters to minimize the RMSE (root mean square error) between predicted and measured soil and crop response data over a 5-year experimental period. Details of the model inputs and calibration procedures are given by Li et al. (in press), and the model parameter values used here are those derived from the previous contribution.

3. Crop rotations, traffic and tillage options explored

Dryland farmers normally grow one crop each year, either in winter or summer, with a fallow in the alternate season, but there is an increasing trend toward opportunity cropping (Freebairn et al., 1986). Opportunity cropping refers to growing a second crop in the same year if there is sufficient water stored in the soil after harvest to support the second crop. In this study, three cropping systems were selected for long-term simulation: continuous wheat, continuous sorghum and a wheat–sorghum opportunity cropping. Within each cropping system, four traffic and tillage management practices were simulated: controlled traffic zero tillage (CZT), controlled traffic stubble mulch (CSM), wheeled zero tillage (WZT) and wheeled stubble mulch (WSM). The wheeled practice was considered to represent normal 'random traffic' for field operations, and the controlled traffic practice represented systems where all wheel traffic was confined to permanent uncropped lanes. Zero tillage had no tillage operations and all fallow weed control was achieved with herbicides. Normal tillage weed control practices were used for stubble mulch. These included primary tillage at 120 mm depth after receiving more than 30 mm rainfall over 6 days, and secondary tillage at a shallower depth after receiving more than 20 mm rainfall over 6 days with a minimum of 30 days between consecutive tillage operations. Planting was assumed to occur after 1st June and 31st October each year for continuous wheat and sorghum cropping systems, respectively, and after less than 25 mm of rainfall occurred over 7 days. For opportunity cropping, a minimum of 60 mm of plant available water accessible from planting depth was required before planting either wheat or sorghum with planting dates between 1st May and 1st August, and 1st October to 31st January for wheat and sorghum, respectively. These criteria were

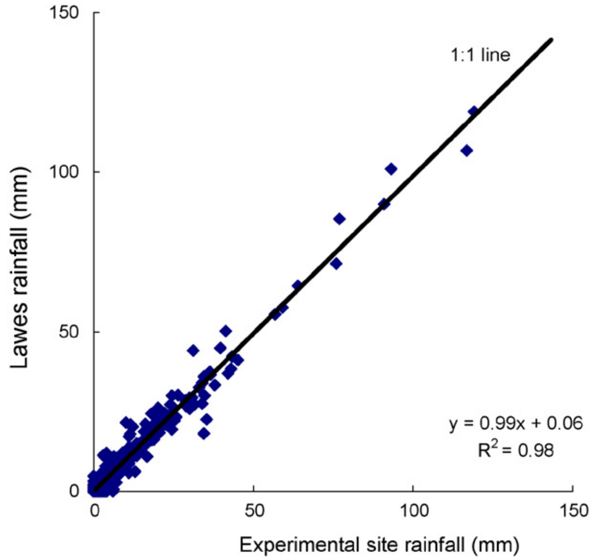

Fig. 1. Comparison of daily rainfall between experimental site and Lawes weather station from 1995 to 1999.

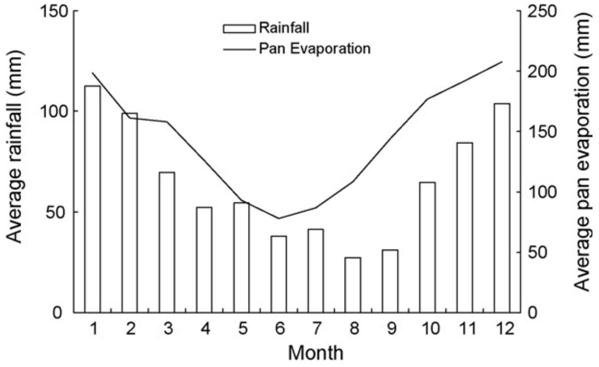

Fig. 2. Average monthly rainfall and pan evaporation of Lawes weather data during a 44-year long-term prediction from 1957 to 2000.

used to simulate the number and timing of tillage operations and crop planting dates which would occur under normal farm practice over a 44-year-period, using archived weather data.

4. Results of model simulation

Simulation results shown in this section apply to three common cropping systems used in Queensland dryland farming. Traffic and tillage management had a different effect on the performance of each cropping system, but there were some similarities. All comparisons below are quantitative and not statistically based.

4.1. Continuous wheat cropping system

4.1.1. Probability distribution

Probability distributions for annual runoff, annual soil loss, crop yield and annual drainage for continuous wheat cropping system are shown in Fig. 3. Runoff was substantially lower in all years for controlled traffic practices than for wheeled practices (Fig. 3a). Runoff was also lower when zero tillage was applied under controlled traffic. Predicted runoff was zero for 20% of the years under CZT.

Zero tillage, regardless of traffic practice, produced less soil loss than stubble mulch tillage (Fig. 3b). Predicted soil loss was zero for 70% of the years for CZT, but more than 5 t/ha of soil loss was predicted for 90% of the years for WSM treatment.

The model predicted the greatest wheat yield for CZT and the lowest wheat yield for WSM (Fig. 3c). Controlled traffic increased median crop yield by between 12% and 28% compared to the wheeled treatment. A break-even yield (cost of production = value of crop) of 2000 kg/ha (Freebairn and Gupta, 1990), would have been exceeded in approximately 55% and 80% of the 44 years for CSM and CZT, respectively.

Reduced runoff led to more rainfall drainage through the soil profile. This was predicted to occur in less than 40% of the years for WSM, but increased to 90% of years for CZT.

Table 1
Predicted mean annual runoff, soil loss, drainage and yield for continuous wheat cropping system over 44 years from 1957 to 2000

Treatment	Runoff (mm)	Soil loss (t/ha)	Drainage (mm)	Yield (kg/ha)
CZT	65.6	0.2	129.9	2939
CSM	87.5	16.2	61.8	2746
WZT	163.2	1.5	46.1	2598
WSM	171.3	30.8	9.0	2361

4.1.2. Annual analysis

Controlled traffic reduced average annual runoff and soil loss by 54% and 49%, respectively, and resulted in a 15% increase in wheat yield compared to wheeled practice. Controlled traffic produced more drainage through the soil profile due to improved infiltration. Stubble mulch, regardless of traffic practice, significantly increased soil loss compared with zero tillage. In general, CZT produced less annual runoff and soil loss, and increased crop yield and drainage for continuous wheat cropping system (Table 1).

The dynamic effect of traffic and tillage on wheat yield during the 44-year simulation of a continuous wheat cropping system is shown in Fig. 4. The vertical axis indicates the difference in yield of CZT, CSM and WZT compared with WSM which is represented by the horizontal axis or zero yield increase. In almost all cases, the yield of CZT, CSM and WZT was greater than WSM. The greatest yield increase for all years was under CZT with mean yield increase of 525 kg/ha.

4.1.3. Average monthly distribution

Average monthly rainfall and runoff, soil loss, crop and residue cover and plant available water are presented in Fig. 5. Runoff accompanying rainfall events between December and May was almost double for the wheeled treatments compared to controlled traffic (Fig. 5a). Runoff was lower for all treatments in the winter months when there was less rainfall. No soil loss was predicted between August and November for any of the treatments. Both stubble mulch treatments had greater soil losses

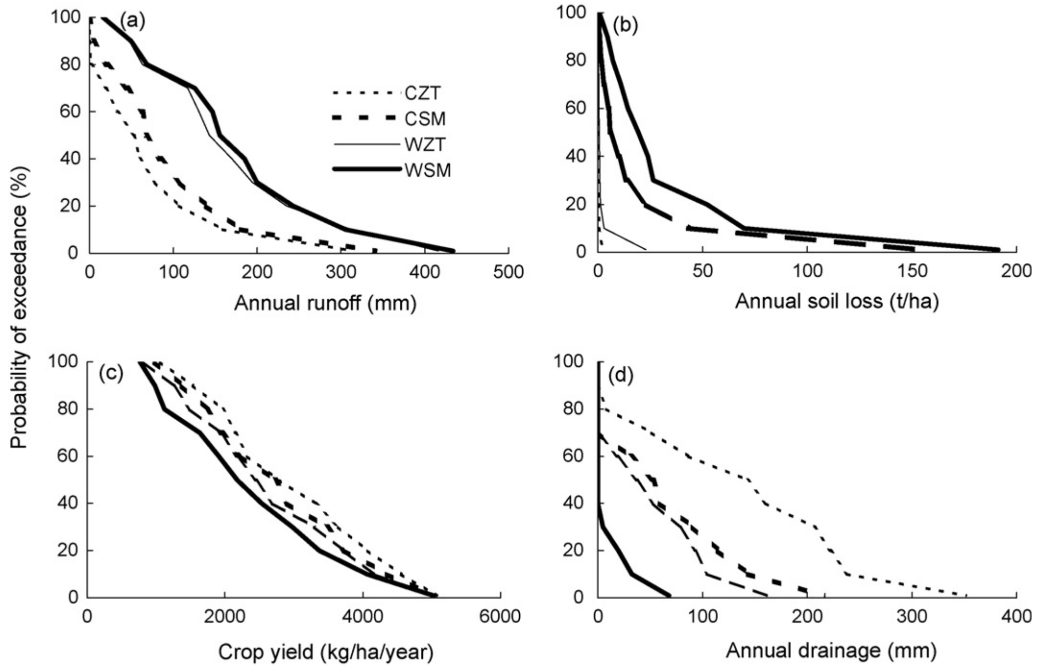

Fig. 3. Probability of exceedance for annual runoff (a), soil loss (b), crop yield (c) and drainage (d) for continuous wheat cropping system from 1957 to 2000.

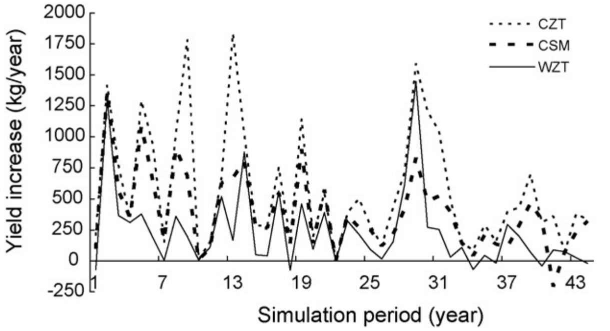

Fig. 4. Yield increase simulated from 1957 to 2000 for continuous wheat cropping systems for CZT, CSM, and WZT practices compared with WSM. The yields of three treatments are relative to WSM.

between December and August (Fig. 5b), as crop cover was removed by harvest in November, and residue cover was reduced by tillage operations between harvest and planting in June (Fig. 5c). The greater residue surface cover of zero tillage corresponded with the much lower soil loss in all months compared to stubble mulch. Plant available water reached its lowest value (less than 50 mm) for all traffic and tillage practices prior to harvesting in October. CZT had the lowest runoff and soil loss, and the greatest soil water and surface cover in all months compared with other practices.

4.2. Continuous sorghum cropping system

4.2.1. Probability distribution

Exceedance probability distributions for annual runoff, soil loss, crop yield and annual drainage for four traffic and tillage practices under a continuous sorghum cropping system are shown in Fig. 6. Controlled traffic practice produced less annual runoff in all years (Fig. 6a). Zero annual soil loss was predicted for 40% of the years under CZT, but some soil loss was predicted in every year under WSM (Fig. 6b). Controlled traffic resulted in greater crop yield and more annual internal drainage than wheeled practices (Fig. 6c and d) due to less runoff.

4.2.2. Annual analysis

Controlled traffic produced less annual runoff and soil loss than wheeled practices under continuous sorghum (Table 2). The effect was similar to that in continuous wheat, with CZT producing less runoff and soil loss but greater crop yield and drainage than the other three treatments.

The dynamic effect of traffic and tillage on sorghum yield during the 44-year simulation of continuous sorghum production is shown in Fig. 7. The vertical axis indicates sorghum yield increase for each of CZT, CSM and WZT compared with WSM which is the conventional practice and is represented by the horizontal axis in Fig. 7. The mean yield increase was greatest for CZT.

4.2.3. Average monthly distribution

Average monthly rainfall and runoff, soil loss, crop and residue cover and plant available water are presented in Fig. 8. Controlled traffic produced less runoff in each month compared with wheeled practices (Fig. 8a). All systems were more susceptible to soil loss between September and December than in other months (Fig. 8b). Maximum soil loss occurred in December, at more than 8 t/ha for WSM practice. Stubble mulch had lower levels of crop and residue cover in all months, with the least in November (Fig. 8c). Plant available water was greater than 100 mm in most months for all traffic and tillage practices except for wheeled treatments from February to May. Controlled traffic

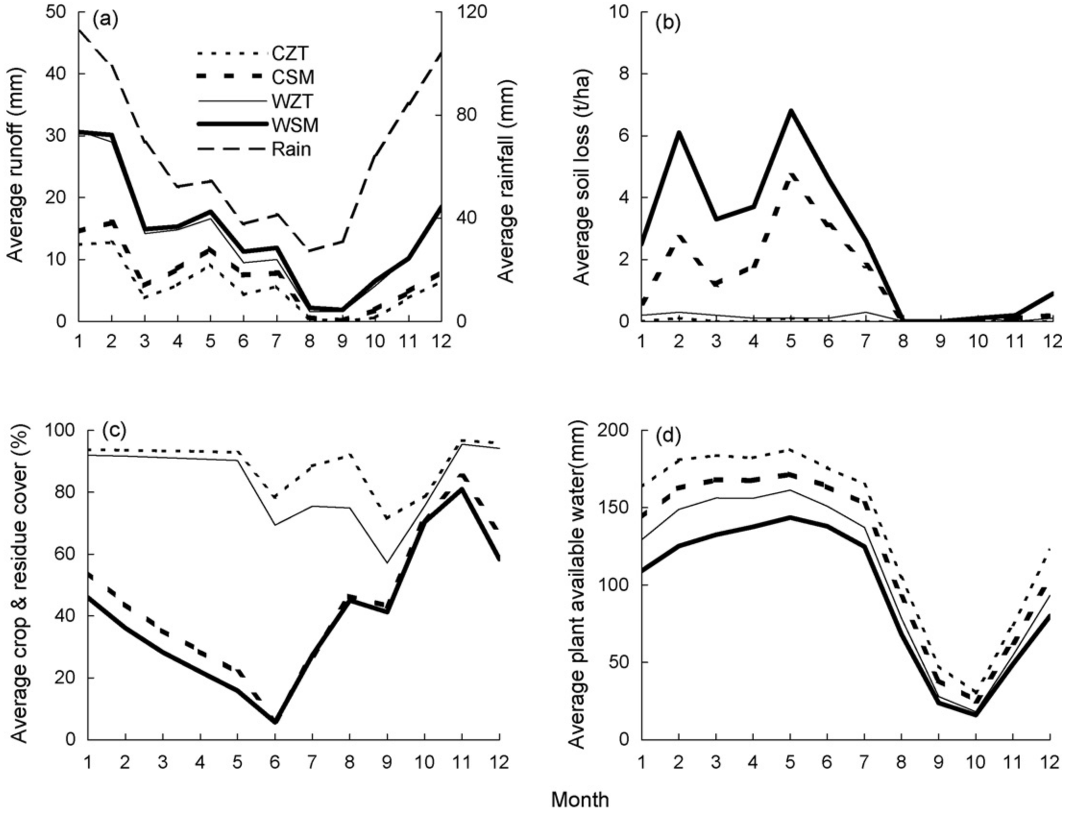

Fig. 5. Average monthly rainfall and runoff (a), soil loss (b), crop and residue cover (c) and plant available water (d) for continuous wheat cropping system from 1957 to 2000.

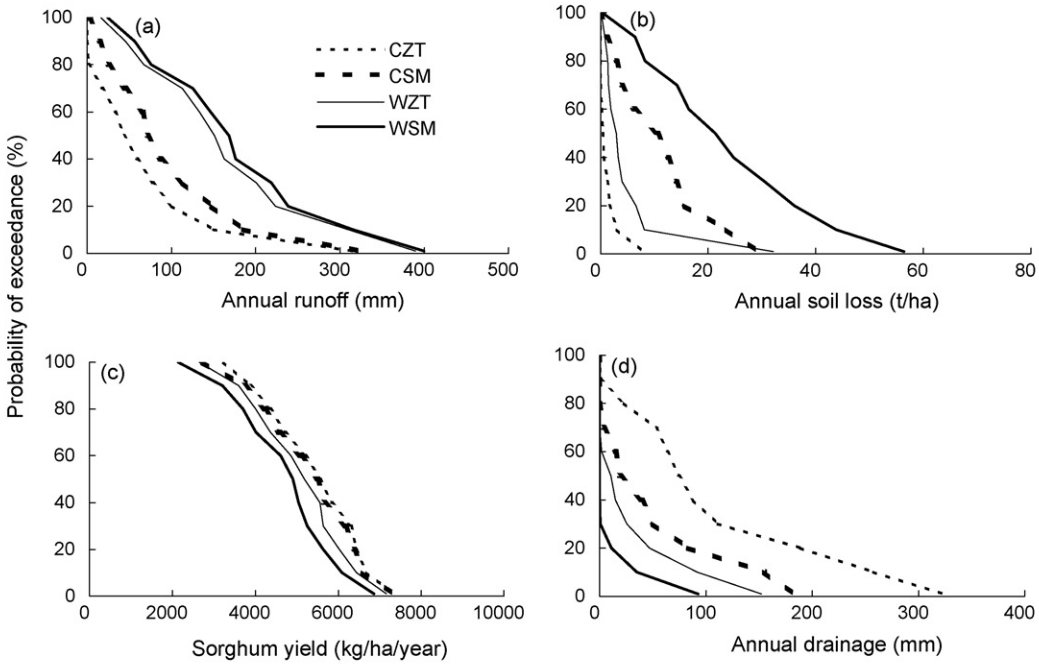

Fig. 6. Probability of exceedance for annual runoff (a), soil loss (b), crop yield(c) and drainage (d) for continuous sorghum cropping system from 1957 to 2000.

always had more plant available water compared with wheeled soil. CZT produced the least runoff and soil loss and greatest plant available soil water for all months.

4.3. Opportunity wheat–sorghum cropping system

4.3.1. Probability distributions

Probability distributions for annual runoff, soil loss, crop yield and annual drainage for all traffic and tillage practices for the opportunity wheat–sorghum cropping system are presented in Fig. 9. Wheat yield was more sensitive to traffic and tillage than sorghum yield in all years. Internal drainage was predicted to occur in <50% of the years for CZT, but this reduced to 10% of the years for WSM (Fig. 9e), and water loss from the wheeled treatments was via greater runoff (Fig. 9a).

4.3.2. Annual analysis

Controlled traffic resulted in a greater summer sorghum cropping intensity due to greater plant available soil water content. Average yields of wheat and sorghum increased by about 29% and 10%, respectively (Table 3). Under controlled traffic, drainage and crop yield were higher, and runoff and soil loss were lower.

4.3.3. Average monthly distribution

Average monthly rainfall, runoff, soil loss, crop and residue cover and plant available water are presented in Fig. 10 for the wheat–sorghum opportunity cropping system. Maximum soil loss occurred in January, July and December. WSM gave the greatest soil loss, while CZT resulted in zero soil loss for half the years, and less than 0.3 t/ha for the remaining years. Crop and residue cover was more evenly maintained throughout the years for all traffic and tillage practices compared to the continuous cropping systems, but stubble mulch gave less crop and residue cover compared with zero tillage. Controlled traffic always produced greater plant available water.

Table 2
Predicted mean annual runoff, soil loss, drainage and yield for continuous sorghum cropping system over 44 years from 1957 to 2000

Treatment	Runoff (mm)	Soil loss (t/ha)	Drainage (mm)	Yield (kg/ha)
CZT	63.0	1.1	103.7	5446
CSM	92.0	10.5	45.8	5329
WZT	160.8	4.1	27.6	5066
WSM	174.2	23.4	9.2	4721

5. Discussion

5.1. Effect of traffic and tillage on runoff and soil erosion

Controlled traffic produced less runoff during the 44-year simulation compared with wheeled practices under all three cropping systems. Zero tillage also reduced runoff, but the effect was smaller than that of controlled traffic. Combining the two in the CZT treatment resulted in the greatest reduction in runoff among all traffic and tillage practices. This is consistent with the

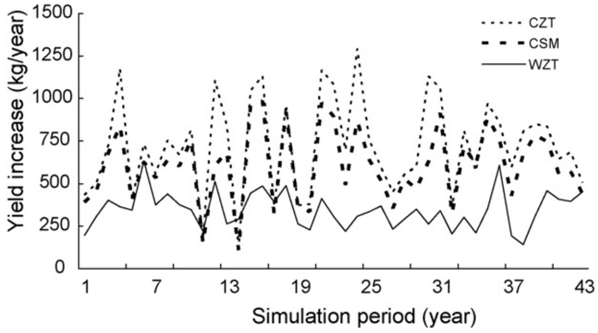

Fig. 7. Yield increase simulated from 1957 to 2000 for continuous sorghum cropping systems for CZT, CSM and WZT practices compared with WSM. The yields of three treatments are relative to WSM.

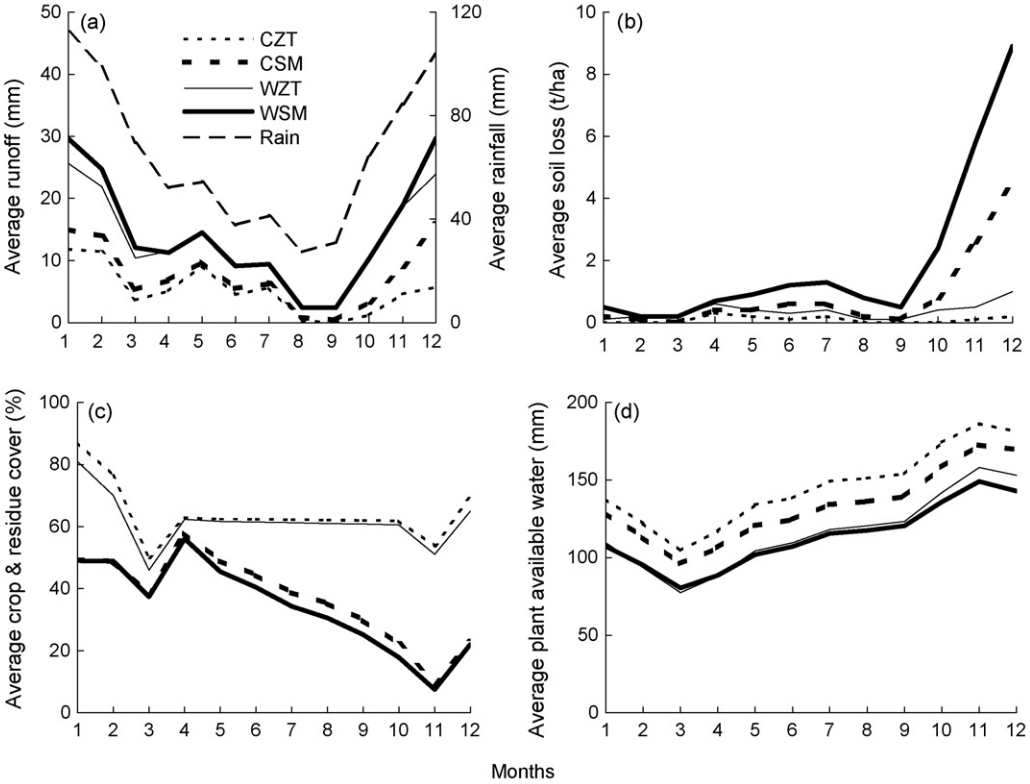

Fig. 8. Average monthly rainfall and runoff (a), soil loss (b), crop and residue cover (c) and plant available water (d) for continuous sorghum cropping system from 1957 to 2000.

field experiments in Australia on a cracking clay soil (Rohde and Yule, 1998a) and in China on a loam soil (Wang, 2000). Yule (1998) also noted that controlled traffic was adopted quickly in northern Australia due to its runoff control benefit. These results suggest that runoff would have been reduced by 50% if controlled traffic had been applied over the last 44 years.

A possible adverse consequence of better infiltration with controlled traffic is the possibility of increased loss of water through the soil profile as drainage, which could exacerbate the leaching of NO_3 and rising water tables (Freebairn and Gupta, 1990). Controlled traffic produced the greatest drainage through the soil profile, particularly for continuous wheat and continuous sorghum cropping systems. Drainage was reduced significantly in opportunity wheat–sorghum cropping system, because with two crops in 1 year, transpiration accounted for a larger proportion of the water balance. The reduction in runoff and increased drainage through the soil profile for controlled traffic compared with WSM under continuous wheat cropping system is illustrated in Fig. 11a and b. For both CZT and WSM, higher cropping intensity of the wheat–sorghum opportunity system resulted in greater transpiration and lower drainage than the corresponding tillage system in continuous wheat (Fig. 11c vs. Fig. 11a and Fig. 11d vs. Fig. 11b). In both cropping systems, transpiration was higher and drainage was lower for the controlled traffic system. The greater cropping intensity under controlled traffic systems illustrates the benefit resulting from improved infiltration and reduced runoff.

The soil profile was driest under the opportunity cropping system, compared with continuous cropping systems. This was expected as the two crops use more plant available water than one crop. The result was consistent with the results from a field experiment by Rohde and Yule (1998b).

Drainage is difficult to measure experimentally, and the model provided a simple method to examine the effects of traffic and tillage management on drainage from different cropping systems. Drainage was not measured in this study, but the trends in predicted drainage for a wheeled black earth soil were similar to those using the CREAMS model under random traffic (Silburn and Freebairn, 1992).

Soil loss is largely dependent on runoff and soil surface cover (Freebairn and Wockner, 1986; Blevins and Frye, 1993). CZT produced the maximum amount of crop and residue cover among all practices, and thus the least runoff and soil loss for all cropping systems. In contrast, WSM had the greatest runoff and the minimum level of surface cover and produced the greatest soil loss.

Opportunity cropping provided a more even distribution of crop and residue cover throughout the year (Fig. 10c) compared with other continuous cropping systems (Figs. 5c and 8c) and therefore soil loss was less. Lower cropping intensity and longer fallow for continuous wheat or sorghum cropping systems resulted in more soil loss in those months with less residue cover.

5.2. Effect of traffic and tillage on plant available water and crop yield

Improved infiltration in controlled traffic treatments increased soil water storage in the soil profile, resulting in predicted yield increases. Soil was wetter in all months under continuous wheat and continuous sorghum, compared with the opportunity cropping system, except for the months between July and December for the continuous wheat.

Crop yield was influenced more by traffic management than tillage for all cropping systems in this simulation study, which is consistent with the results from other field experiments (Radford and Yule, 1998; Rohde and Yule, 1998b; Tullberg et al., 2001). Controlled traffic produced greater average plant available water

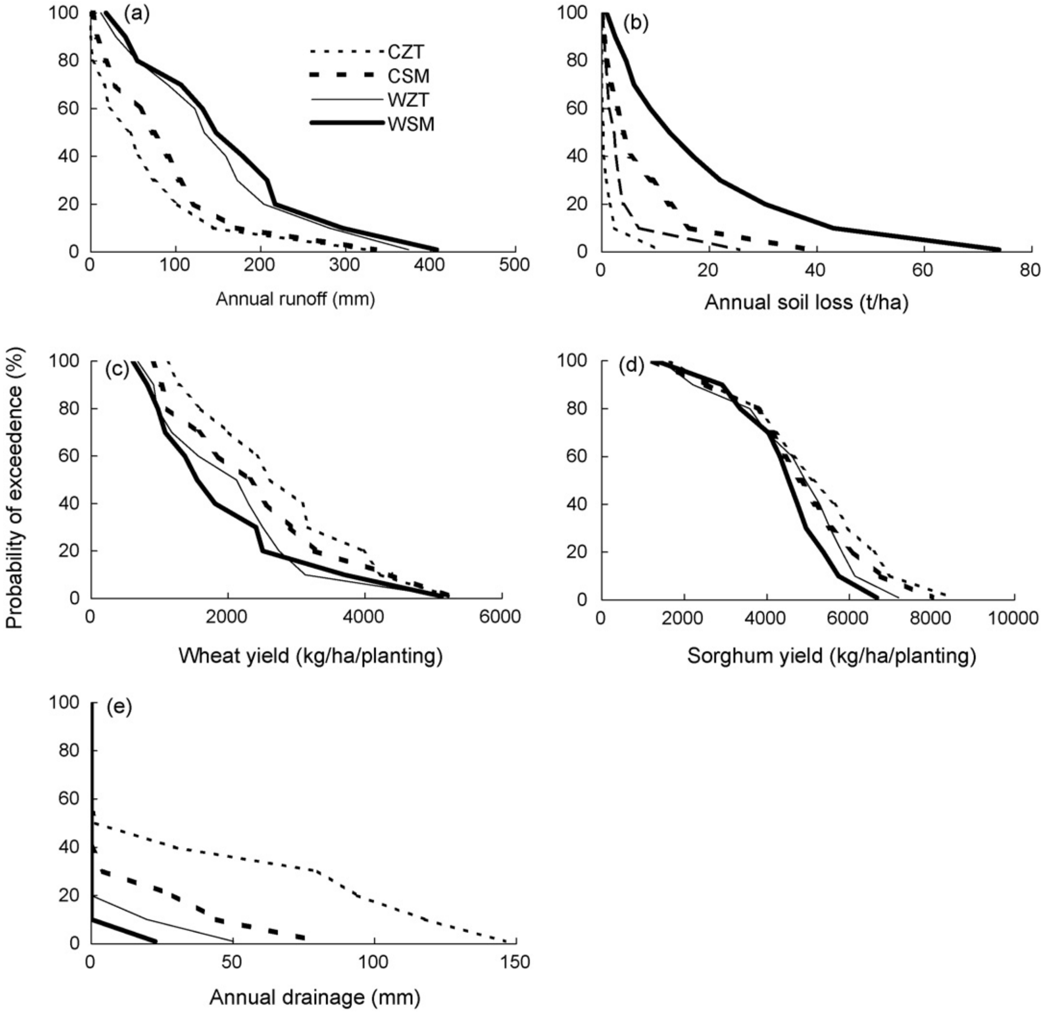

Fig. 9. Probability of exceedance for annual runoff (a), soil loss (b), crop yield (c and d) and annual drainage (e) for opportunity wheat–sorghum cropping system from 1957 to 2000.

in all months and for all cropping systems compared with wheeled practices (Figs. 5d, 8d and 10d), but summer crops were less affected by traffic and tillage management because, as pointed out by Freebairn et al. (1989), they receive more rainfall during the growing season in this climate.

Controlled traffic allowed for greater cropping intensity than wheeled practices. For instance, sorghum could be planted in an opportunity cropping system in 91% and 85% of the 44-year-period under controlled traffic and wheeled practices, respectively (Table 3). Mean annual yield (all years considered regardless of whether planted) of wheat or sorghum declined under the opportunity cropping system, but total yield increased due to the greater number of crops over 44 years.

CZT gave the best performance among all traffic and tillage practices for all cropping systems. There was less runoff, more infiltration and water storage under controlled traffic, although it was possible to produce high drainage losses through the soil profile if crops were unable to use the water. Higher intensity cropping increased the proportion of transpiration in the water balance and reduced the amount of drainage.

Probability distributions for annual runoff and soil loss only described the range of occurrences for each system, and are not necessarily predictions. For instance, high intensity rainfall on dry and residue covered soil does not necessarily produce runoff or erosion. Presentation of average monthly distributions of runoff, soil loss, soil water and crop and residue cover provided

Table 3
Predicted mean annual runoff, soil loss, drainage and yield for opportunity wheat–sorghum cropping system over 44 years from 1957 to 2000

Treatment	Runoff (mm)	Soil loss (t/ha)	Drainage (mm)	Yield (kg/ha)			
				Wheat	YP	Sorghum	YP
CZT	61.3	1.0	39.4	2749	25	5065	40
CSM	83.8	7.4	11.9	2427	25	4756	40
WZT	144.2	3.6	4.6	2084	24	4624	39
WSM	159.1	18.7	0.5	1938	25	4328	35

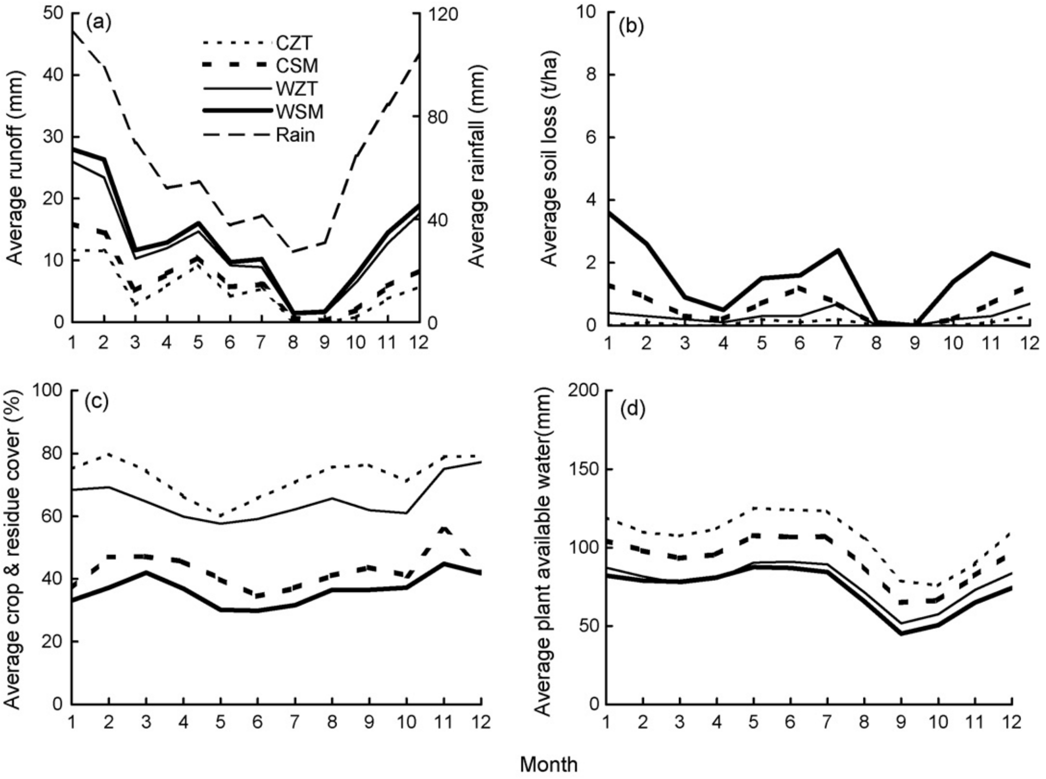

Fig. 10. Average monthly rainfall and runoff (a), soil loss (b), crop and residue cover (c) and plant available water (d) for wheat–sorghum opportunity cropping system from 1995 to 1999.

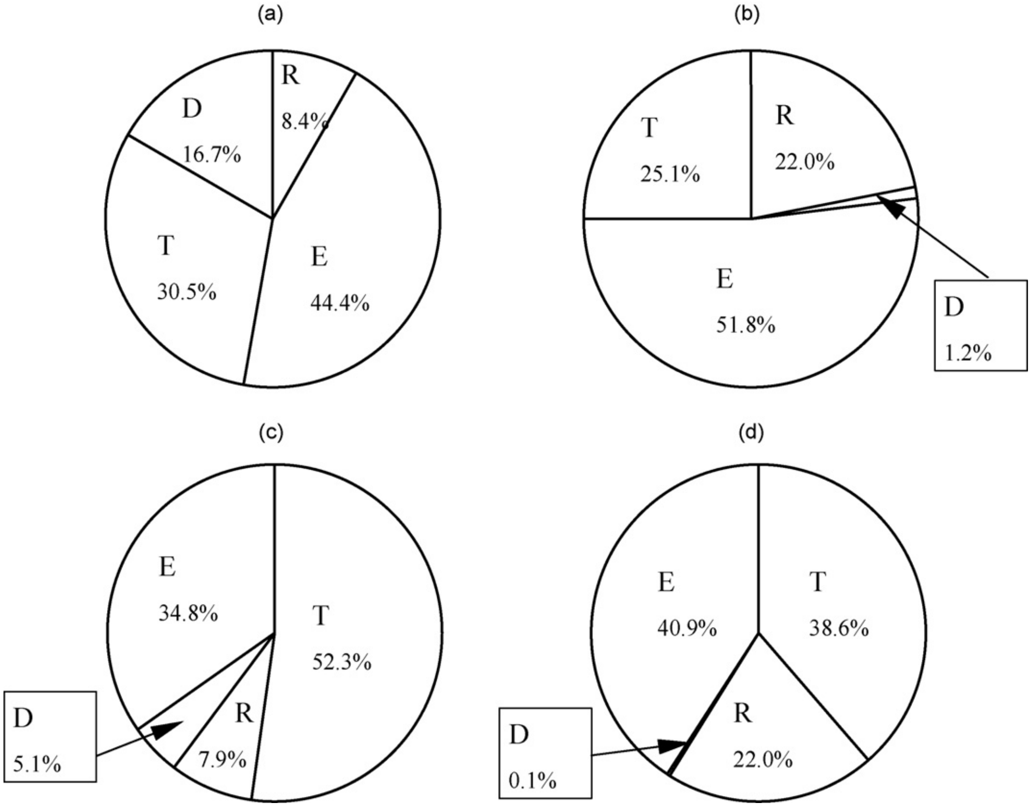

Fig. 11. Mean annual water balance for continuous wheat cropping system of CZT (a) and WSM (b), and for opportunity wheat–sorghum cropping system of CZT (c) and WSM (d). D – drainage; R – runoff; E – evaporation; T – transpiration.

a more transparent way to understand soil erosion problems and solutions.

6. Conclusion

Long-term traffic and tillage effects for three cropping systems in Southeast Queensland, Australia were simulated over a 44-year-period using the PERFECT simulation model and historical weather data. The following conclusions were drawn.

(1) Controlled traffic produced less runoff and soil erosion, but more plant available water and greater crop yields in these three cropping systems, compared with wheeled practice. Zero tillage also had a similar impact when compared with stubble mulch tillage, but this tillage effect was smaller than the traffic effect.

(2) The best (highest yield) traffic and tillage management was CZT (controlled traffic zero till) in a high cropping intensity rotation under opportunity cropping, and the worst was WSM (wheeled stubble mulch) with continuous wheat.

(3) Controlled traffic resulted in greater water infiltration and lower runoff than wheeled treatments. Under opportunity cropping, most of the extra infiltrated water was available to, and used by the crop, resulting in higher yields, but in continuous one-crop systems (wheat or sorghum), the improved infiltration resulted in greater loss of water through the soil profile as drainage.

(4) Soil erosion and drainage were not calibrated against experimental data in part I of this contribution due to limitations in the experimental data available from this study, but long-term simulation with this model appears to provide useful information on water balance and soil erosion.

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