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Runoff, soil loss, and nutrient transport from cropping systems on Red Ferrosols in tropical northern Australia

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Abstract. Runoff, soil loss, and nutrient loss were assessed on a Red Ferrosol in tropical Australia over 3 years. The experiment was conducted using bounded, 100-m^2 field plots cropped to peanuts, maize, or grass. A bare plot, without cover or crop, was also instigated as an extreme treatment. Results showed the importance of cover in reducing runoff, soil loss, and nutrient loss from these soils. Runoff ranged from 13% of incident rainfall for the conventional cultivation to 29% under bare conditions during the highest rainfall year, and was well correlated with event rainfall and rainfall energy. Soil loss ranged from 30 t/ha.year under bare conditions to <6 t/ha.year under cropping. Nutrient losses of 35 kg N and 35 kg P/ha.year under bare conditions and 17 kg N and 11 kg P/ha.year under cropping were measured. Soil carbon analyses showed a relationship with treatment runoff, suggesting that soil properties influenced the rainfall runoff response. The cropping systems model PERFECT was calibrated using runoff, soil loss, and soil water data. Runoff and soil loss showed good agreement with observed data in the calibration, and soil water and yield had reasonable agreement. Long-term runs using historical weather data showed the episodic nature of runoff and soil loss events in this region and emphasise the need to manage land using protective measures such as conservation cropping practices. Farmers involved in related, action-learning activities wished to incorporate conservation cropping findings into their systems but also needed clear production benefits to hasten practice change.

Additional keywords: erosion, nutrient loss, PERFECT, Red Ferrosols, runoff, simulation models, tropical agriculture.

Introduction

Ferrosols are important cropping soils in North Queensland (Kent and Tanzer 1983; Laffan 1988; Malcolm *et al*. 1998) and throughout Australia (Cotching 1995). On the Atherton Tablelands, crop and grazing industries have utilised these soils for >90 years, while at Lakeland Downs (250 km north of the Atherton Tablelands), significant cropping development has occurred since 1960 (Grundy and Heiner 1994). The majority of these freely draining soils were developed for broadacre, rainfed cropping systems, with a large percentage on sloping topography between 1 and 6% (Shepherd and MacNish 1989). Substantial areas are also used for dairy pasture production, particularly on the higher slopes. These soils are deeply weathered and strongly leached. In their virgin state, they are low in exchangeable cations, contain ~4% organic carbon (C) (0–0.10 m), with a pH of 6.0 decreasing with depth (Isbell *et al*. 1976); however, with cultivation the organic matter drops to <2% and the cation exchange capacity (CEC) declines, principally due to organic matter decline (Warrell *et al*. 1984).

In the region, high intensity storms at the start of the wet season and the summer-dominant rainfall distribution provide conditions for high runoff and soil erosion. This has been exacerbated by historical land preparation practices, which include frequent disc and rotary tillage. For example, a survey of cropping lands of the Atherton and Herberton shires, following major storms in November 1985, showed soil losses of up to 405 t/ha on conventionally cultivated and unprotected land (East 1985). Significant reductions in erosion were found where land had been protected with soil conservation works and crops with well-developed canopies. Land resource surveys (Kent and Tanzer 1983; Laffan 1988) also identified land degradation, including soil erosion, as major impediments to agricultural sustainability in the region. Generally, soil conservation practices (physical and cultural) to reduce soil loss have been slowly adopted, with 1998 estimates for the Atherton shire showing that only 36% of the area requiring protection by contour banks actually has soil conservation structures (Malcolm *et al*. 1998). Use of surface cover and reduced tillage or zero tillage technologies was also minimal, even though theses practices have been shown to be productive in small plot studies (Younger *et al*. 1987) and improve soil properties (Prove *et al*. 1990).

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In 1994, farmers on the Atherton Tablelands formed the Conservation Cropping Group (CCG) (Coyle *et al*. 2001) to identify and implement more sustainable cropping practices using action learning processes. The group identified that insufficient information existed on soil erosion, compaction, and fertility decline associated with conservation tillage practices in their area. They supported an on-station experiment evaluating different soil management practices and impacts on runoff, soil loss, crop yield, and soil properties as being complementary to their on-farm studies. However, it was also realised that field experiments can only provide information over a limited time period.

Simulation modelling is a powerful tool which can extrapolate information from short time periods to make predictions of the impacts over longer timeframes. The USDA Hillslope Erosion Model was applied to this site with some success (Cogle *et al*. 2003), but was unable to fully incorporate the impacts of cropping cycles on erosion and runoff. The model PERFECT (Productivity, Erosion, and Runoff Functions to Evaluate Conservation Techniques) was developed to provide such long-term predictions of the major effects of land management (Littleboy *et al*. 1989, 1999). PERFECT has been used successfully to evaluate the long-term impacts of soil erosion on cropping systems on the Darling Downs, Australia (Littleboy *et al*. 1992), and to evaluate the long-term impact of a range of soil management practices in the Alfisols of south-central India (Littleboy *et al*. 1996, Cogle *et al*. 1996). Merritt *et al*. (2003), in a major review of erosion and sediment transport models, recognised that PERFECT was a potentially valuable tool for assessing the impacts of cropping systems on water balance, erosion, and crop yield. Their review also noted that calibration against local field data was important for any application of the model.

The objectives of our study were (*i*) to assess the impacts of different tillage practices on runoff, soil erosion, and nutrient loss on the Red Ferrosols of North Queensland, and (*ii*) to apply the cropping systems model PERFECT to provide information for long-term sustainable land management on the Atherton Tablelands.

Materials and methods

Study site

The study (Fig. 1) was on Kairi Research Station (17°20′S, 145°57′E; 715 m ASL), run by the Department of Primary Industries, Qld. It is on the Atherton Tablelands, ~90 km from Cairns in North Queensland.

Soil

The soil type, a Red Ferrosol, is representative of much of the agricultural soils on the Atherton Tableland. It was formed on basalt flows and is found on level to gently undulating plains and rises (Malcolm *et al*. 1998). The soil profile class, *Tolga*, is a deep red, structured, uniform clay soil with a well-drained profile (Laffan 1988). The clay percentage ranges between 50% (surface) and 75% (1 m), and pH_{water} between 6.6 (surface) and 5.9 (1 m). Bulk density ranges between 1.1 g/cm^3 (0–0.15 m) and 1.3 g/cm^3 (0.50–1.20 m).

Fig. 1. Experimental site at Kairi Research Station.

Climate

Long-term average annual rainfall is 1233 mm, with most falling in the summer months between November and May, providing distinct wet and dry seasons. This seasonality is emphasised by the rainfall seasonality index (RSI) of 0.74 determined by Yu (1998), where an RSI >0.13 indicates a summer-dominant wet season. Average monthly maximum temperatures are 20.8–28.7°C and minimum temperatures 11–19.5°C.

Two rainfall pluviometers were installed at the site to measure rainfall amount and intensity, with two manual rain gauges to validate the logged measurements. An official Bureau of Meteorology automatic weather station on the research station records sunshine hours, temperature (min., max., soil), evaporation, and windspeed.

Experimental design and analysis

The experiment covered an area of ~0.5 ha, incorporating 12 plots (20 by 5 m) divided into four treatments, each with three replications, using an incomplete randomised block design. The treatments were: Conventional tillage (CT), Reduced tillage (RT), Grass pasture, and Bare. The slope at the experimental site was 6%. CT used one pass of a disc plough during the dry season followed by offset discs just before planting rains in November or December. RT consisted of two passes of a chisel plough trailing a dead rod; one pass was made during the mid dry season (July–September) and the other just before planting rains, for weed control. The cropping sequences under CT and RT were peanuts (*Arachis hypogea*) in 1998–99 and maize (*Zea mays*) in 1999–2000 and 2000–01.

The Grass plots were converted from RT in 1997–98. The grass was *Braccharia decumbens*. After the establishment year, the plots were mulched (grass mown) approximately twice per year, with all cuttings retained on the plots.

Bare plots were first disc-ploughed early in the season, followed by an offset disc, followed by a rotary hoe to substantially destroy soil structure. No crops were planted in these plots, and weeds were controlled using herbicides. This treatment was chosen as an extreme treatment that represented the worst case for runoff, soil loss, and nutrient loss; however, during the project cycle, it was evident that some district farmers had soil in a similar state of preparation at times during the wet season, e.g. for early planting of potatoes.

Ripping to 0.55–0.65 m was performed in all cropped plots as well as the Bare plots every 2–3 years in July to alleviate compaction and hard-setting problems. Herbicides such as glyphosphate and atrazine were used for weed control in maize crops, and glyphosphate and Fusillade were used in peanuts. Pest and disease management in peanuts was performed according to local recommendations of the Department of Primary Industries (Michael Hughes pers. comm.).

Sowing times varied depending on the incidence/timing of the first rains. Generally, peanut and maize crops were sown between late November and late December. Actual dates were 23 December 1998 (peanuts), 31 January 2000 (maize), and 29 November 2000 (maize). Maize and peanuts were sown at a row spacing of 0.90 m, giving plant densities of 65 000/ha for maize and 110 000/ha for peanuts.

At sowing, all fertiliser was banded at ~60 mm beside the seed. Rates (/ha) were: for maize 80 kg nitrogen (N), 25–30 kg phosphorus (P), and 25 kg potassium (K); for peanuts 40 kg P and 40 kg K.

Measurements

Cropping

Plant density, vegetative yield, and grain yield for maize crops were recorded. Sampling involved randomly selecting two 5-m rows within each plot. Plant counts were made and cobs were harvested. Vegetative yield was measured from 2.5 m of each 5-m row. Cobs were de-husked and shelled by hand and grain moisture was determined. Vegetative yield was dried and weighed.

Peanuts were hand-harvested from a randomly selected 2-m row for all plots. Plant counts were taken and the nuts were removed from the plants. Nuts were cleaned of soil and weighed in the shell. After weighing, kernels were sorted by quality indices according to local grading standard of the Peanut Marketing Board.

Grass plots were sampled on a yearly basis using a randomly located quadrat and grass was cut at ground level using hand shears. Field weights were recorded and samples were oven-dried. Cover measurements (combined canopy and contact) were estimated visually at intervals during the course of the wet season.

Soil samples, to a depth of 1 m, were collected using either a hand auger or a hydraulically mounted soil corer during the growing season. Gravimetric moisture content was determined.

Runoff and sediment collection

Each plot was ~100 m^2 (20 m long by 5 m wide) and bunded at the top by a contour bank and the sides by man-made soil banks. At the bottom was a trough leading into a 4-L tipping bucket with a dual-tipping mechanism. Each tipping bucket was fitted with a magnetic reed switch that sent a magnetic pulse back to one of two Campbell dataloggers each time a tip occurred. In addition, the two pluviometers were connected to the dataloggers.

Runoff water and sediment samples were taken after events. At the front of each tipping bucket was a splitter device, which collected a subsample (~22 mL) of runoff water from each second tip of the tipping bucket. Runoff water was collected from the splitter reservoir within 6 h of runoff and refrigerated. Bedload sediment was collected from the bottom of the troughs and oven-dried at 40°C. At times, continuous light rain and runoff made definition of runoff events difficult for sampling discrete events for bedload and suspended load. In these circumstances, sampling of bedload and suspended load occurred several times during a period of up to 3 days. Identification of events for analysis was made after reviewing the logger data taken at 6-min intervals. Subsamples of runoff water, suspended sediment, and bedload were also taken for subsequent chemical analysis for total N and total P.

Physical and chemical analysis

Suspended load

A measured volume of unfiltered runoff water was filtered through a pre-washed and weighed glass fibre filter paper (0.7 mm). The weight of dried sediment on the filter paper was measured. From both the volume of water and the sediment weight, the concentration of sediment in the water was calculated (Eaton *et al*. 1995).

Total nitrogen and phosphorus in runoff water

An aliquot (10 mL) of well-mixed, unfiltered water was digested in sulfuric acid and potassium sulfate with mercuric oxide added as catalyst. The digest was then diluted and analysed using automated continuous flow colourimetric techniques (Bran+Luebbe 1990). During digestion, nitrogenous (except nitrate-N) compounds are converted to ammonium ions, while phosphorus compounds are converted to orthophosphate ions.

Total N and C in soil were determined by combustion at 1300°C in a LECO CNS-2000 analyser (LECO Corp., St. Joseph, MI, USA). Total P was determined using wet digestion.

Statistical analyses

Analysis of runoff logger data was undertaken using internal Department of Natural Resources and Water programs (Cyril Ciesiolka, pers. comm.). A measure of rainfall erosivity (EI$_{30}$) was determined using the EI$_{30}$ calculation of Wischmeier and Smith (1978).

Data were analysed using GENSTAT (GENSTAT 5 Committee 1993), and least significant differences (l.s.d. at $P = 0.05$) are presented where the ANOVA was significant.

An enrichment ratio (ER) for C and for N was calculated after Hashim *et al*. (1998) assuming a topsoil depth of 0.10 m.

$$\mathrm{ER} = \text{nutrient concentration in sediment/nutrient concentration in topsoil} \quad (1)$$

Modelling

The cropping systems model PERFECT (Littleboy *et al*. 1989, 1999) was run using data from the Kairi runoff plots. PERFECT simulates plant–soil–water management dynamics in agricultural systems on a daily time-step. Inputs include daily weather, soil properties, tillage practices, and crop parameters. Outputs include water-balance components (e.g. runoff, drainage, evaporation, transpiration), soil erosion, and crop growth as impacted by designated management practices (e.g. tillage type and time, planting time).

The plant-available water capacity of the Ferrosol (*Tolga* series) (Table 1) at the site was determined based on soil survey data (Malcolm *et al*. 1998) and previous site sampling undertaken at wet and dry soil moistures. Soil parameters adjusted during calibration were porosity, saturated moisture, runoff curve number, and K_{sat}. The soil evaporation parameters CONA (stage 1 evaporation) and U (stage 2 evaporation) were set at 4.0 and 8.5, respectively. The leaf area index (LAI) crop model within PERFECT was used to simulate crop growth. Crop parameters adjusted during calibration were root depth, daily root growth, and the proportion of growing season at a specified LAI and growing degree-days.

Outputs from the model (predicted) were plotted against observed values. An r^2 and regression equation for the relationship between predicted and observed, regressed through the origin, was calculated using an Excel spreadsheet. A further r^2 based on the 1 : 1 line is presented as the standard for model calibration.

Long-term model runs

Long-term PERFECT simulations (1905–2000) were completed using a climate dataset for Atherton obtained from APSRU, Toowoomba. Long-term daily evaporation was required by the model, and as long-term records are not available, it was calculated using the Priestley–Taylor equation with a weighted temperature value from the data and adjusted using a bare soil albedo value where appropriate.

The long-term predictions were based on a range of potential and actual crop rotations, and on identification of the impact of different slope and soil characteristics. The model allows a planting window to be determined for each crop, and these were identified in consultation with local agronomists (Table 2). Local erosion control recommendations (Rudd and Cummins 1988) were used for contour bank spacing, and all simulations used an 80-m slope length for both 2 and 5% slopes. The impact of surface structure degradation was evaluated by increasing the input parameter curve number from 73 to 83 for selected predictions.

Table 1. Soil water parameters (final) used for calibration/validation of the *Tolga* series Ferrosol at Kairi Research Station

Depth (mm)	Airdry	Lower limit	Upper limit	Saturation	K_{sat} (mm/h)
	(% vol)				
200	12.0	25.0	39.0	47.0	30.0
600	12.0	26.0	39.0	50.0	60.0
1000	12.0	29.0	37.0	51.0	60.0
	Other model parameters				
4.0	Stage II soil evaporation Cona				
8.5	Stage I soil evaporation limit, U (mm)				
73.0	Runoff curve number CN2 (bare soil)				
35.0	Reduction in CN at 100% cover				
25.0	Max reduction in CN due to tillage				
325.0	Cumulative rainfall (mm) to remove roughness				
0.07	MUSLE K Factor (metric units)				

Results

Rainfall

Monthly rainfall between 1998 and 2001 showed peaks during February substantially above long-term average February rain (Fig. 2); however, during other months, rainfall approximated the long-term average.

Runoff

Annual runoff between 1998 and 2001 was greatest for Bare treatments and least for Grass treatments (Table 3). There were significant treatment differences ($P < 0.05$) in 1998–99 between tillage treatments, but in later years these differences did not occur.

Approximately four major runoff events occurred each wet season during the course of the project. Two examples of treatment responses to event rainfall are presented. The first example (Fig. 3*a*) is for March 2000. It occurred 10 days after antecedent rainfall of 94 mm and 39 days after planting, which meant that crop cover had developed. The CT and RT runoff responses were similar. The second example (Fig. 3*b*) is for November 1998 and illustrates the runoff response 10 days after a tillage event for CT, RT, and Bare treatments and antecedent rainfall of 96 mm, but before planting. This meant there was no crop cover for CT and Bare treatments. Runoff response was Bare, CT > RT > Grass.

To summarise the individual event responses, several relationships were plotted and regressions calculated. In summary, event runoff increased with event rainfall as shown

Table 2. Planting windows used for long-term runs

Crop	Start of planting window	Finish of planting window
Peanuts	26 Nov.	15 Jan.
Maize	26 Nov.	31 Jan.
Sorghum	1 Sept.	20 Dec.
Potatoes	1 April	1 July
Sugar	1 May	31 Dec.
Summer grass	17 Sept.	31 Dec.

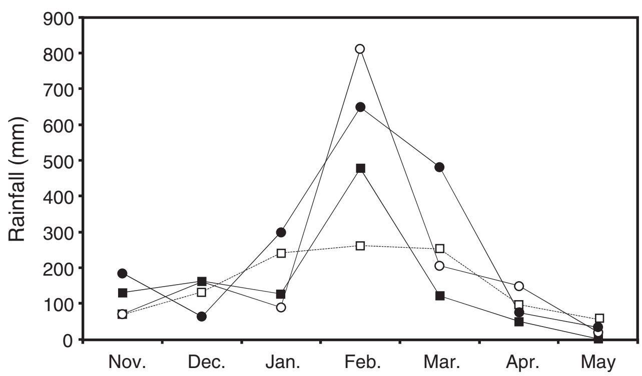

Fig. 2. Rainfall between November and May for 1998–2001 at the plot study site. (1998–99 ●; 1999–2000 ○; 2000–01 ■; long-term average □).

Table 3. Annual runoff (mm) and total erosion (t/ha) between 1998 and 2001
Within columns, values followed by the same letter are not significantly different at $P = 0.05$

	1998–99		1999–2000		2000–01	
	Runoff	Erosion	Runoff	Erosion	Runoff	Erosion
Rainfall:	1675 mm		1500 mm		1032 mm	
Bare	479a	30.6a	277a	15.2a	157a	10.4a
Conventional tillage	215b	6.2b	167b	5.6b	24b	0.5b
Reduced tillage	121c	4.2b	151b	4.3bc	25b	0.3b
Grass	70c	1.7b	39c	0.3c	20b	0.0b
l.s.d. ($P = 0.05$)	81	8.3	51	4.5	11	3.7

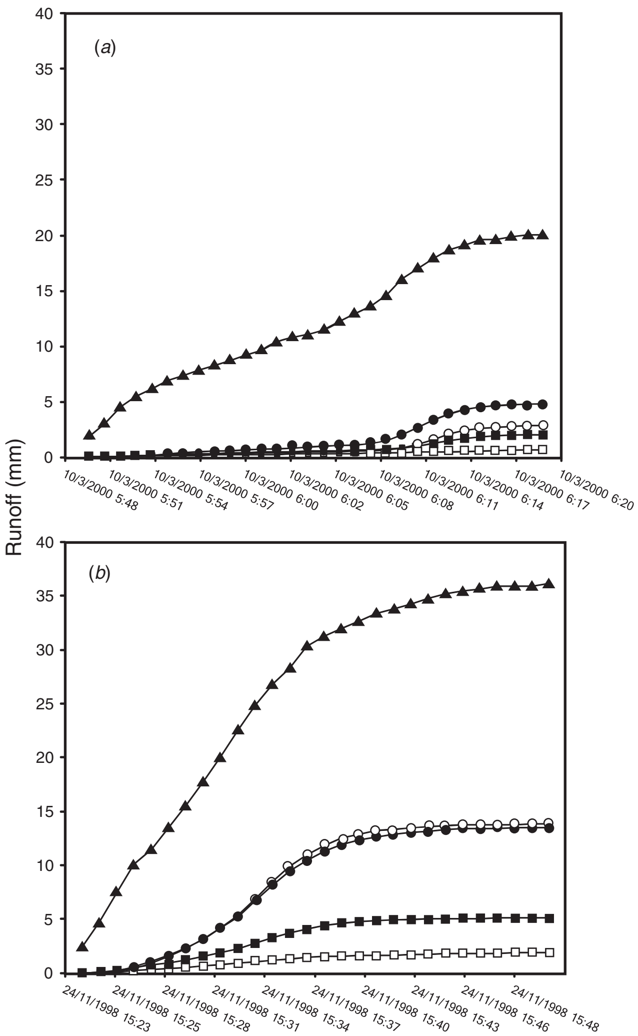

Fig. 3. Runoff (mm) *v.* time for (*a*) the March 2000 event and (*b*) the November 1998 event. Rainfall ▲, Bare ●, CT ○, RT ■, Grass □ plots.

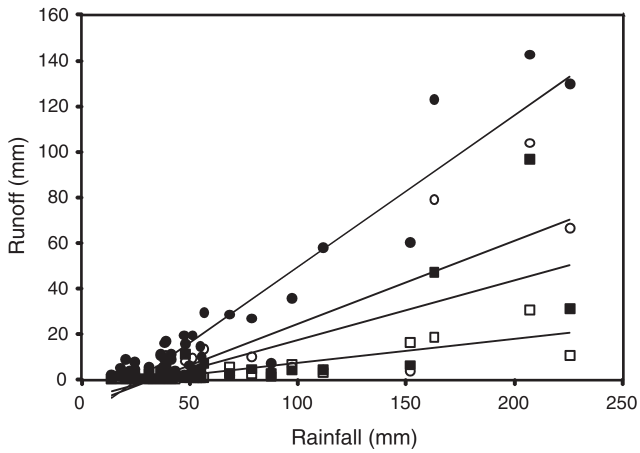

Fig. 4. Event runoff (mm) *v.* event rainfall (mm) between 1998 and 2001. Bare ●, Conventional tillage ○, Reduced tillage ■, Grass □ plots.

(Fig. 4), with the slopes of each of the regression lines significantly different for each treatment (Table 4). The slope of the lines also suggested that runoff was initiated after rainfall of between 26 mm (Bare) and 33 mm (RT) on these soils, noting that runoff cannot be negative. Greater runoff for a similar EI_{30} was also shown (Table 4) for the Bare treatment than both cropped treatments (CT, RT), which produced more than the Grass treatment.

Groundcover

Groundcover was different for the four treatments throughout the experiment, with the Bare and Grass treatments constantly at 0% and 100% cover, respectively. The two crop treatments (CT and RT) had cover that varied depending on crop stage and tillage. At planting, CT had 0% cover, while the RT treatment had 25–35% straw cover in each year. The straw cover rapidly decomposed over ~4 weeks and crop growth rates were not different between CT and RT (data not shown). Four weeks after planting, crop cover was ~35% in each of the years, and maximum crop cover reached 95% for peanuts after 12 weeks and 60% for maize after 8 weeks.

Soil erosion

Annual soil loss was greatest for the Bare treatments and least for Grass plots. There was no significant difference ($P > 0.05$) in soil loss for the two tillage treatments (Table 3). The differences across years reflect the respective different rainfall characteristics; however, it is noticeable that in 1998–99, when runoff was significantly different ($P < 0.05$) between CT and RT, there were no significant differences in soil erosion.

The slope of the relationship between event soil loss (kg/ha) and runoff was significantly different for all treatments

($P < 0.05$) (Fig. 5, Table 4), suggesting that soil treatment changed the erosion response of the Ferrosol.

Suspended load was compiled for all three seasons after combining continuous events as described in the methods. The ratio of suspended load over bedload varied between 0.00 and 1.29 across all event runoffs (data not shown). Suspended load concentrations ranged between 136 and 5598 mg/L.

Nutrient loss

Total N and total P losses from plots in 1998–99 and 1999–2000 showed a similar response to runoff and soil erosion (Table 5). Nutrient analyses were not undertaken in 2000–01. Phosphorus loss was significantly higher from Bare treatments, with a similar comparison for N loss except in 1998–99. Concentrations for the samples taken during the four events in each of the 1998–99 and 1999–2000 seasons were in the ranges 0.222–12.100 mg/L for total N (unfiltered), 0.001–8.880 mg/L for total P (unfiltered), 0.003–2.297 mg/L for ammonium-N, 0.012–1.267 mg/L for nitrate-N, and 0.002–0.302 mg/L for phosphate-P.

Carbon, nitrogen, and phosphorus

Soil C (LECO) was 12.4, 13.6, 14.1, and 16.9 g/kg for Bare, CT, RT, and Grass treatments, respectively (l.s.d. ($P = 0.05$) 0.14). Soil C (LECO) was therefore significantly reduced by increased tillage and the removal of the grass pasture in the 3 years of cropping. Labile C (C1) determinations indicated levels of 0.77, 0.89, 1.03, and 1.52 g/kg in the Bare, CT, RT, and Grass treatments, respectively (I. Webb, unpublished data).

There was no significant difference between Bare, CT, and RT treatments for soil N (LECO), but the Grass treatment was significantly higher than all other treatments (Table 6). No differences in total P concentrations existed across treatments.

Table 4. Equations and statistics for regressions between runoff, rainfall, EI_{30}, and runoff as % Rainfall

The statistics column represents the results from pairwise testing; for each comparison, values followed by the same letter are not significantly different at $P = 0.05$. n.a., Not applicable

Treatment	Equation	Statistics
	Runoff v. rainfall (adjusted $r^2 = 80\%$)	
Bare	Runoff = 0.67 rainfall – 17.37	a
Conventional tillage	Runoff = 0.36 rainfall – 11.87	b
Reduced tillage	Runoff = 0.26 rainfall – 8.57	c
Grass	Runoff = 0.11 rainfall – 3.32	d
	Runoff v. EI_{30} (adjusted $r^2 = 76\%$)	
Bare	Runoff = 2.23 EI_{30} – 15.31	a
Conventional tillage	Runoff = 1.30 EI_{30} – 11.95	b
Reduced tillage	Runoff = 0.92 EI_{30} – 8.45	c
Grass	Runoff = 0.37 EI_{30} – 3.20	d
	Runoff as %rainfall v. EI_3 (adjusted $r^2 = 57\%$)	
Bare	Runoff as %rainfall = 0.786 EI_{30} – 13.92	a
Conventional tillage	Runoff as %rainfall = 0.521 EI_{30} – 1.65	ab
Reduced tillage	Runoff as %rainfall = 0.357 EI_{30} – 1.32	bc
Grass	Runoff as %rainfall = 0.173 EI_{30} – 0.13	c
	Soil loss v. runoff (adjusted $r^2 = 86\%$)	
Bare	Soil loss = 51.23 runoff + 734.20	a
Conventional tillage	Soil loss = 20.22 runoff + 367.68	b
Reduced tillage	Soil loss = 19.06 runoff + 242.92	c
Grass	n.a.	

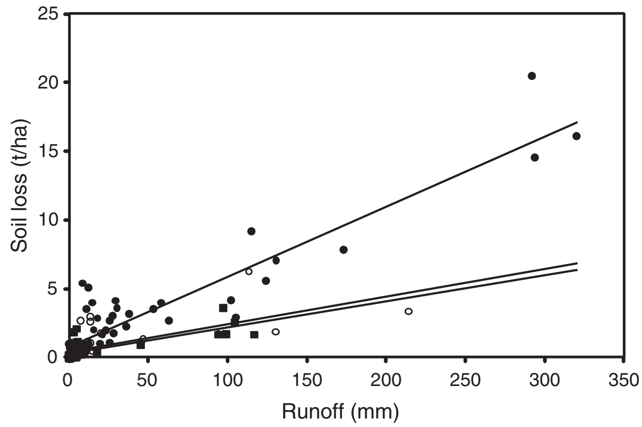

Fig. 5. Soil loss (kg/ha) *v.* runoff (mm) for events between 1998 and 2001. Bare ●, Conventional tillage ○, Reduced tillage ■ plots.

Table 5. Total nitrogen (N) and phosphorus (P) loss (kg/ha) from the treatments

Within columns, values followed by the same letter are not significantly different at $P = 0.05$

	1998–99		1999–2000	
	N	P	N	P
Bare	35.3a	35.6ab	11.2b	10.9c
Conventional tillage	17.4ab	11.5b	4.6a	4.1a
Reduced tillage	9.8b	8.9b	3.6a	3.3ab
Grass	4.8b	3.1b	0.6a	0.4b
l.s.d. ($P = 0.05$)	18.1	9.9	4.8	3.5

Table 6. Nitrogen (N) (Leco) and phosphorus (P) concentrations in the top 0.10 m for all the treatments, and enrichment ratios (ER) for 1998–99 and 1999–2000

Values followed by the same letter are not significantly different at $P = 0.05$. n.s., Not significant

	Leco N (%)	ER (N) 1998–99	ER (N) 1999–00	Total P (%)	ER (P) 1998–99	ER (P) 1999–00
Bare	0.1335a	0.72	0.46	0.14	0.88	0.54
Conventional tillage	0.1393a	2.10	0.62	0.14	1.34	0.53
Reduced tillage	0.1437a	1.68	0.60	0.13	1.50	0.54
Grass	0.1602b	1.97	0.70	0.13	1.37	1
l.s.d. ($P = 0.05$)	0.0148	–	–	n.s.	–	–

Enrichment ratios (Table 6) were calculated based on the total N and P loss during each of the two wet seasons for the major runoff events. These ERs were lower in 1999–2000 than 1998–1999. Generally, the ER of the Bare treatment was lower than that for other treatments.

Crop and vegetative yield

Crop yields (Table 7) were not significantly different between CT and RT treatments, with >7.9 t/ha of total dry matter (grain plus vegetative yield) produced in each year. Total dry matter in the Grass plots was >9.7 t/ha and greater than that produced in the cropped plots.

Runoff modelling

Predicted and observed daily runoff for each treatment is shown in Fig. 6. The model explained 63–92% of the variation in daily runoff. The calibration was based on >40 events over 3 years and includes a range of treatment responses to incident rainfall. For example, during this period, the Bare treatment had up to 25% runoff, the Grass treatment 2–3% runoff, and cropped treatments showed intermediate responses depending on crop stage. Rainfall during the 3 years showed peaks in February substantially above the long-term average February rain (Fig. 1), but at other times rainfall followed the long-term average.

Annual runoff showed a good relationship between predicted and observed, with 91% of the variation being explained by the PERFECT model (Fig. 7).

Soil erosion modelling

The model explained 87% of the variation in event erosion for the Bare treatment over the 3 years. Measured event soil loss for CT and RT treatments was low (data not shown). Annual erosion was predicted well for the Bare treatment and for the cropped treatments (Fig. 8). The model explained 88% of the variation.

Table 7. Crop yields (kg/ha) for 1998–99 to 2000–01 (not applicable to Bare treatment)

Peanuts are presented as nut-in-shell; grain yield is at 14% moisture; DM, dry matter. There were no significant differences. n.a., Not applicable

	Peanuts 1998–99	Maize 1999–2000	Maize 2000–01
Conventional tillage			
Grain	5751	3596	6222
Vegetative yield	5256	4323	6600
Total DM	10 593	7919	12 822
Predicted total DM	8092	14 593	15 482
Reduced tillage			
Grain	5453	3626	6412
Vegetative yield	5213	4581	6750
Total DM	11 081	8206	13 162
Predicted total DM	8092	14 593	15 535
Grass			
Total DM	17 030	9660	n.a.
Predicted total DM	17 479	14 880	n.a.

Soil water modelling

The modelling for soil water showed a less definitive result than runoff and erosion model outputs, in part due to the limited number of soil water profiles taken during the measurement period. For the Bare, RT, and CT treatments, predicted soil water was always higher than observed data for both total profile water (Fig. 9) and individual depth increments (data not shown). The Grass treatment, however, had smaller differences between predicted and observed, in that the predicted total soil water profile was sometimes lower than observed data. Overall, the model explained 69%, 73%, 73%, and 52% of the variation for soil water measurements for Bare, CT, RT, and Grass treatments, respectively.

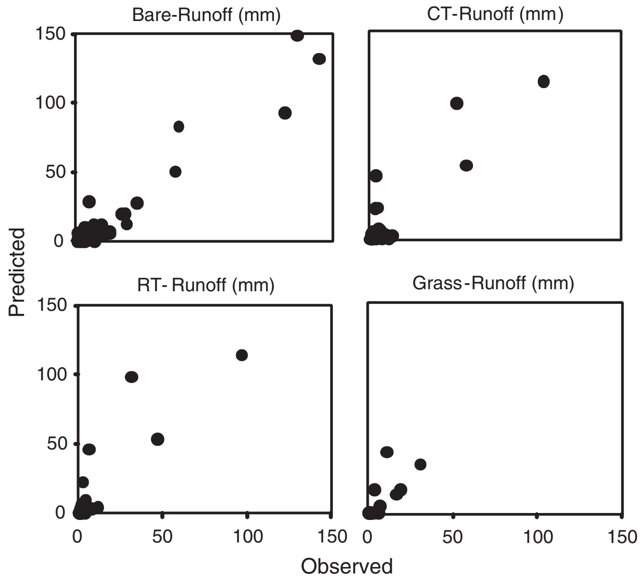

Fig. 6. Predicted *v.* observed runoff for Bare, Conventional tillage (CT), Reduced tillage (RT), and Grass plots over 3 years.

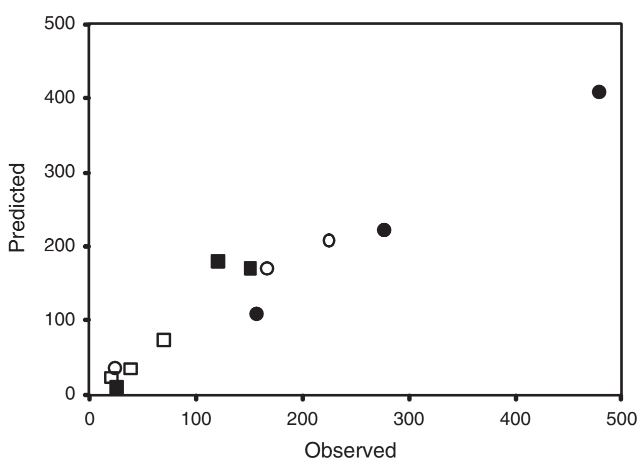

Fig. 7. Annual runoff (mm) for all treatments plotted as predicted versus observed. Bare ●, Conventional tillage ○, Reduced tillage ■, Grass □ plots.

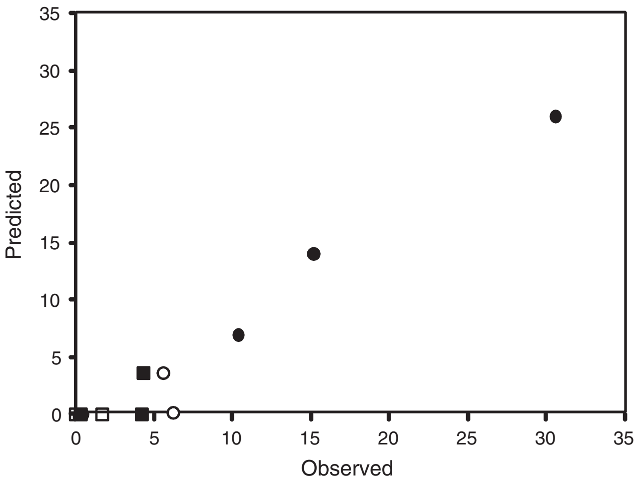

Fig. 8. Annual erosion (t/ha) for all treatments plotted as predicted versus observed. Bare ●, Conventional tillage ○, Reduced tillage ■, Grass □ plots.

Yield modelling

Predicted yields (Table 7) were broadly similar to observed yields, except in 1999–2000 when grain yields were reduced by rats.

Long-term predictions

Predicted long-term estimates of runoff, drainage, and soil erosion are shown in Table 8. Over 1905–2000, runoff for reduced tillage maize was lower than for other managements and crops, and rotations with potatoes increased the estimated runoff, presumably because of the window of bare soil during the early wet season. Changing the curve number from 73 to 83 in bare soils increased runoff by >50%.

The drainage estimates are provided as indicators of the annual recharge to groundwater. There was a range of some 181 mm between the lowest drainage (467 mm) and the highest (648 mm) under the range of crop and soil managements.

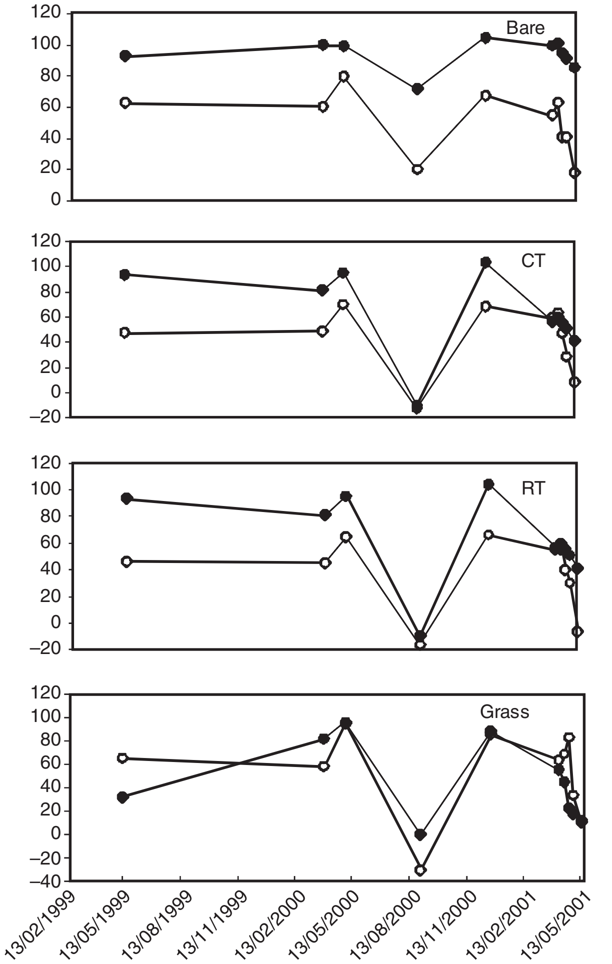

Fig. 9. Predicted (●) and observed (○) total profile soil water for Bare, Conventional tillage (CT), Reduced tillage (RT), Grass plots over 3 years.

Discussion

Runoff was greatest from the Red Ferrosols on the Atherton Tablelands under land management practices with the lowest surface cover. This was true for individual events, as shown by

Table 8. Long-term outputs for runs between 1905 and 2001 using the calibrated PERFECT model

Curve number is 73 and slope is 5% unless otherwise stated. Probability of exceedence at 50% and 20% are also provided. CT, Conventional tillage; RT, reduced tillage

	Runoff (mm)			Drainage (mm)			Erosion (t/ha)		
	Av.	50%	20%	Av.	50%	20%	Av.	50%	20%
CT peanuts	82	41	142	622	564	882	2.6	0.4	3.8
RT peanuts	73	33	113	641	584	923	1.8	0.1	1.7
CT maize	71	33	124	621	562	902	1.2	0	1.3
RT maize	53	19	92	648	584	920	0.5	0	0.2
Sorghum/potatoes (CT)	91	45	149	553	478	803	6.1	0.2	1.7
Peanuts/potatoes (CT)	89	48	144	539	459	778	4.7	1.5	5.4
Sugar/potatoes (CT)	81	43	116	467	400	702	2.9	0.4	2.8
Grass/potatoes (CT)	103	53	196	551	484	783	8.3	4.0	14.3
Bare	172	117	291	613	567	819	17.2	11.5	29.2
Bare (curve no., 83)	301	239	449	484	465	650	30.2	24	45
Bare (curve no., 73; 2% slope)	172	117	291	613	567	819	7.4	5.0	12.6

the significant differences in slopes of the regressions between runoff and rainfall, and on an annual basis. Reduced tillage and grass rotations reduced runoff and are sensible practices for this purpose. It should be noted, however, that due to the diversified nature of the cropping industry (e.g. both summer and winter plantings), it is likely that cultivation will occur throughout the year. Hence, agricultural management that combines strategies to reduce the length of time of low soil cover and also structural mechanisms, such as contour banks, is required for sustainable production systems.

The Bare treatment, which was instigated as an extreme treatment to identify the worst-case scenario, also represents soil management commonly implemented for early-season winter crops such as potatoes, and allows an assessment of a range of planting times for conventionally tilled summer crops. Under bare conditions, runoff initiation occurred slightly earlier, as suggested by the lower amount of rain (26 mm) needed for runoff from bare soil, compared with 30–33 mm for the other treatments. This was probably caused by earlier surface soil structure breakdown in the Bare treatment and is supported by calculations showing a lower EI_{30} for runoff initiation under bare conditions. Prove *et al*. (1990) found a similar response using an intensively monitored rainfall simulator experiment on these soils, but concluded that rain-drop impact reduces infiltration by compacting the surface layer rather than by increasing aggregate breakdown.

In contrast to the result for the Bare treatment, it is noticeable that runoff initiation, as distinct from total runoff, was similar for CT, RT, and Grass treatments, suggesting that these plots were subject to other soil properties (past and present) for runoff initiation. These soil properties could include C content and C fraction, soil cover, and surface roughness, or possibly a subsurface constraint to drainage.

Carbon concentrations were higher in treatments receiving greater inputs of organic matter (e.g. Grass, RT; see Table 7) and lower tillage intensity (RT). Runoff was lower from treatments that had greater C concentration (%) and greater amounts of the labile C fraction, C1. Research by Bell *et al*. (1998) identified a positive linear relationship between total C or C1 and final infiltration rate under field rainfall simulation. They found that in Red Ferrosols (including at sites on the Atherton Tablelands), a steady-state infiltration rate of 100 mm/h would occur with 33.5 g/kg of total C and 2.99 g/kg of C1. Our total C and C1 fraction concentrations fall much lower than this, but with the mathematical relationship of Bell *et al*. (1998), we calculated a final infiltration rate of between 25 mm/h (bare) and 41 mm/h (grass). These calculated infiltration rates are in agreement with the trends (Grass runoff << Bare runoff) from our rainfall event runoff data and identify the utility of the mathematical relationship of Bell *et al*. (1998) Our results also showed that the improvements in infiltration under ley cropping sequences in Red Ferrosols in southern Queensland (Connolly *et al*. 1998) are likely in similar soils in North Queensland.

Soil loss was large under the Bare treatment but not under cropping (CT, RT), and there was no treatment difference for annual totals, even though event soil losses showed significant differences. Our results verify the conclusions of East (1985), who reported large soil losses from areas of the Atherton Tablelands under bare conditions early in the wet season, and emphasise the need to protect soils with cover (residue or growing plant cover) during the whole wet season, particularly given the positive relationship we identified between soil loss (kg/ha) and runoff (mm).

The loss of nutrients from agricultural lands is an important issue for both water quality and efficient production. Substantial losses were shown in the 2 years of measurement, equivalent to 25% of applied N and 30% of applied P in the 1998–99 season from the CT treatment. The nutrients transported from the unfertilised Bare treatment illustrated losses representing worst-case soil erosion, and indicate that large amounts of nutrient can move through our landscape. Enrichment ratios were generally low (0.5–1) for N and P. Indeed, these data were several times lower than those in an Alfisol (Kandosol) with a sandy loam surface (Cogle *et al*. 2002). However, Rose and Dalal (1988) reported that ER values are generally low in high clay soils. It should also be noted that while substantial quantities of N and P were transported from our plots, this does not mean that all the nutrient (or sediment) was transported to catchment outlets, as proportions are assimilated spatially throughout the landscape before reaching water courses (Finlayson and Silburn 1996). This has implications for identifying catchment management options to improve water quality, as identified for the Atherton Tablelands by Cogle *et al*. (2000).

Crop yields were similar for cropped treatments, and these results are comparable to those reported by Prove *et al*. (1990), in that growth differences were apparent within some seasons but were not significant in final yields. Similarly, some differences in yield quality were identified but not significant. As Cotching (1995) discusses in his review, these types of yield results make it difficult to promote benefits of changed farming systems to farmers, and are essentially due to the inherently better soil structure of Red Ferrosols compared with other soils (Bridge and Bell 1994). The Conservation Cropping Group recognised this dilemma (Coyle *et al*. 2001) and concluded that 'on going' learning groups consisting of farmers and scientists working towards the common goal of sustainable farming were needed to increase the rate of practice change. The group considered the 'on going' learning group used for this project as an effective model for the development of such regional groups.

Application of the cropping systems model, PERFECT, for Red Ferrosols on the Atherton Tablelands, North Queensland, predicted runoff and soil erosion in good agreement with observed data, and as well, soil water and crop predictions within reasonable ranges.

The importance of cover in reducing runoff and soil erosion was highlighted by model outputs for several cropping systems that result in bare surfaces at key times during the year (e.g. the wet season). Model runs were also undertaken to simulate soil structural decline and the impact of higher slopes. 'Browser', a data presentation tool developed by McClymont *et al*. (2001), was used with our modelled outputs to show the relationship between the different treatments for the long-term predictions for several land managements at the calibrated slope of 5% and curve number of 73. These outputs (Table 8, Fig. 10) show the episodic nature of runoff and soil erosion across a 50-year period, illustrating that while in some years the benefit of

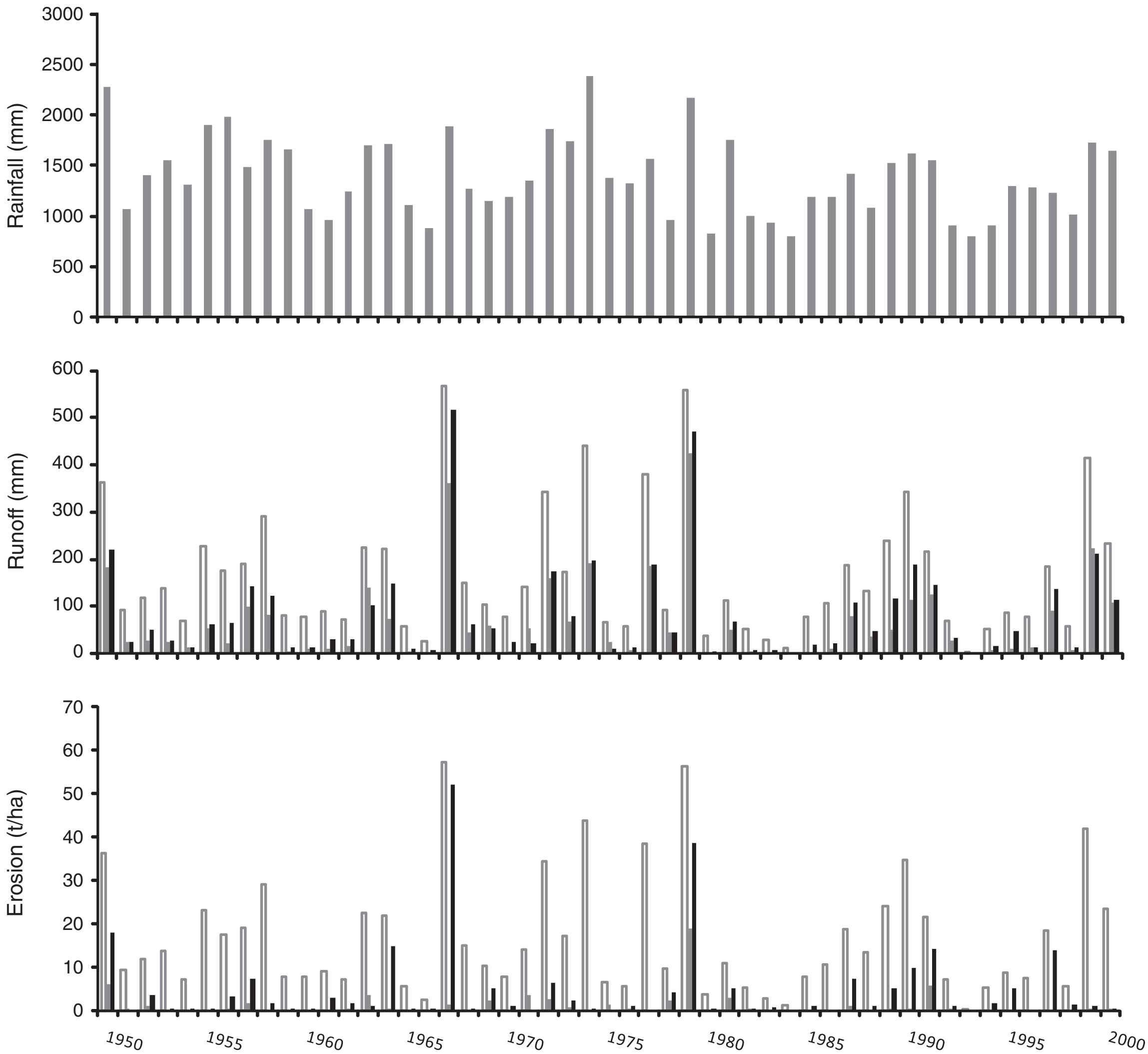

Fig. 10. Long-term outputs for predicted runoff (mm) and erosion (t/ha) compared with annual actual rainfall for a 50 year period for Bare (open bars), Conventional tillage maize (grey bars), and Conventional peanut–potato rotation (black bars) on a 5% slope.

conservation practices may be small, in other years there can be large benefits to protecting the land resource.

Our objective to assess the impacts of different tillage practices on runoff, soil erosion, and nutrient loss showed that benefits will occur in some years with reduced tillage practice. However, it depends on the interaction of rainfall variability and the tillage/crop timing. Extrapolation to the long-term, using the PERFECT model, demonstrated the episodic nature of soil erosion. In many years soil erosion was not significant, but in some years conditions were such to result in large soil erosion losses and, by inference, nutrient loss. These events would have a huge impact on the sustainability of the land resource and, potentially, catchment health.

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