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A Study of Soil Erosion on Vertisols of the Eastern Darling Downs, Queensland. I Effects of Surface Conditions on Soil Movement within Contour Bay Catchments

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Abstract

Effects of soil surface conditions on runoff and soil loss were studied on two major cracking clay soils of the Darling Downs, Queensland. Techniques used to measure soil loss between field contour bays under natural rainfall are described, and the results from 10 contour bay catchments (66 plot years) are presented.

Soil movement was separated into rill, interrill, suspended sediment and channel deposition. Two slope lengths were considered (60 and 35 m), and interrill erosion appeared to be the major source of soil loss.

Runoff and sediment concentration were both inversely related to surface cover and total soil movement was greatly reduced by surface cover. In an annual winter-wheat, summer-fallow system, removal of stubble resulted in soil movement of 29–62 t ha^{-1} $year^{-1}$. Retention of stubble (stubble mulching) reduced soil movement to less than 5 t ha^{-1} $year^{-1}$.

Greater than 75% of the variance in soil movement from single events was explained by surface cover and peak runoff rate. Surface cover is a measure of the surface area protected from soil detachment and entrainment. Peak runoff rate describes the amount of energy or stream power available for detachment and entrainment.

Introduction

Soil erosion is a threat to continued agricultural production in Australia (Anon. 1978). The eastern Darling Downs, Qld, is particularly susceptible to high erosion rates owing to a combination of highly erodible clay soils (Loch and Donnollan 1983), high-intensity summer-dominant rainfall (Rosenthal and White 1980), cultivation of slopes up to 10%, and cropping practices which result in little soil cover during the summer storm period of October to March.

High erosion rates are evidenced by massive episodic siltation of roads, valley floors and flood plains, and the frequent appearance of rills and gullies on the uplands following storm rain. Soil conservation structures (contour banks and grassed waterways) have been implemented on 60% of the 340,000 ha requiring such measures on the eastern Darling Downs. Contour or graded banks are designed to reduce the slope length and thus net erosion (Wischmeier and Smith 1978), yet soil erosion is 'unacceptably high' over most of the region. Research in the USA (McCalla and Army 1961) has indicated that retention of crop residues could reduce soil erosion and runoff while maintaining or improving crop yields.

This study was initiated to determine the amounts of runoff and soil loss occurring on the clay soils of the region, and how these could be influenced by agronomic management. This paper describes the methods used to measure soil

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movement within contour bay catchments, and reports some effects of soil surface conditions on runoff and soil movement. The loss of soil as suspended sediment from the catchments and the effect of rainfall, runoff and cover on sediment concentration are discussed in a subsequent paper by Freebairn and Wockner (1986).

Materials and Methods

Location and Soils

Two catchment trials were established on the eastern Darling Downs (Fig 1). One, located 1·3 km north-east of Greenmount, is 500 m above sea level and has a northerly aspect. The other, at Greenwood, 25 km north-west of Toowoomba, is 470 m above sea level and has a westerly aspect. These sites were selected to represent the two major soils used for grain production on the Darling Downs.

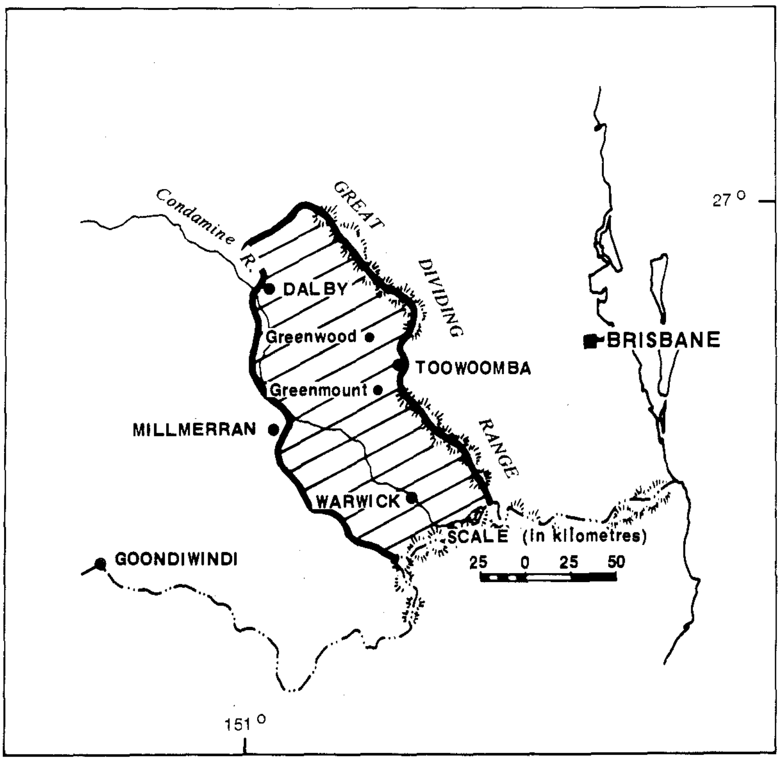

Fig. 1. Location of the sites in the eastern Darling Downs area (Vandersee 1975).

The soil type at Greenmount, a black earth (Ug 5.15; Northcote 1974) derived from basalt is an Udic Pellustert and belongs to the Irving clay soil association (Thompson and Beckman 1959). The soil is strongly self-mulching and exhibits gross cracking in a dry condition. A full description of this soil has been presented by Freebairn and Boughton (1981).

The soil type at Greenwood, a grey clay, Ug 5.16, derived from Walloon sandstone, is a Udic Chromustert and belongs to the Moola clay soil association (Mullins, personal communication). The profile exhibits a distinct linear gilgai between 10 and 30 cm and shows enhanced concentration of salt at approximately

45 cm. The soil is of finer surface structure and less strongly self-mulching than the black earth. The soil is associated with brigalow (*Acacia harpophylla*) and belah (*Casuarina cristata*) vegetation. Surface and profile properties of the two soils are listed in Table 1.

Table 1. Soil properties at the Greenwood and Greenmount experimental sites

Soil properties (0–10 cm depth)	Greenwood site (Moola clay)	Greenmount site (Irving clay)
pH	8·5	8·0
CEC[A] ($C g^{-1}$)	37	68
Coarse sand (%)	10	3
Fine sand (%)	24	13
Silt (%)	13	21
Clay (%)	53	62
0·33 bar water content ($g g^{-1}$)	0·35	0·49
15 bar water content ($g g^{-1}$)	0·20	0·33
PAWC[B], 10–150 cm depth (mm)	186	201

[A] Cation exchange capacity.
[B] Plant available water capacity determined by the difference between the mean wettest and the mean driest profiles in the 1978–84 period.

Rainfall

Annual and summer rainfall (October-March) for the two sites are shown in Table 2. Mean annual rainfall for Greenmount and Acland Bureau of Meteorology stations are included. High-intensity storms are a characteristic of rainfall in the October to March period (Rosenthal and White 1980).

Table 2. Rainfall summary for the two trial sites at Greenmount and Greenwood (1976–84) (mm)

Site year	Greenwood Rainfall W.Y.[A]	Greenwood Rainfall Oct.-Mar.	Greenwood Oct.-Mar. (%)	Greenmount Rainfall W.Y.	Greenmount Rainfall Oct.-Mar.	Greenmount Oct.-Mar. (%)
1976–77	490	382	78	759	497	65
1977–78	639	345	54	728	337	46
1978–79	595	408	69	752	584	78
1979–80	568	453	80	562	463	82
1980–81	861	592	69	902	617	68
1981–82	584	473	81	843	700	83
1982–83	808	348	43	901	357	40
1983–84	869	465	53	894	519	58
Mean 1976–84	676	433	66	793	509	64
Mean 1912–75	673[B]	452	67	723[C]	490	68

[A] Water year October-30 September.
[B] Bureau of Meteorology Station 041000 (Acland).
[C] Bureau off Meteorology Station 041040 (Greenmount).

Treatments

For the first two years at Greenmount (1976–77) three cropping systems were practised — summer cropping, winter cropping and double cropping. In each of the following six years (1978–84), four catchments were devoted to winter crop (wheat) with intervening summer fallow and a fifth to summer crop, at each site. Throughout the summer fallows, a variety of stubble management and fallowing

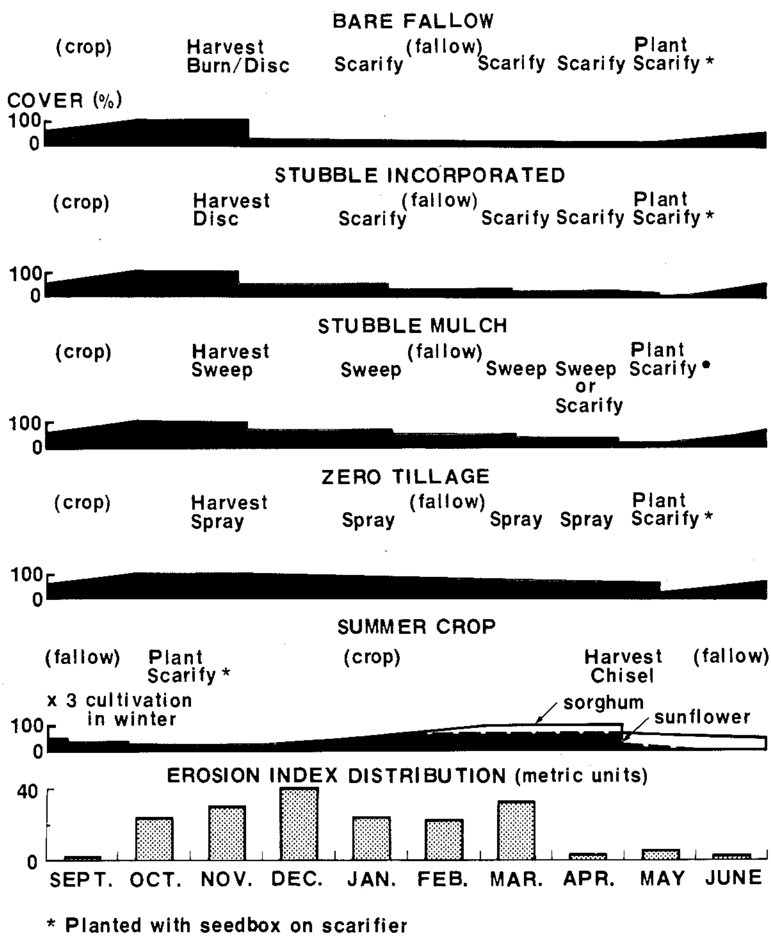

Fig. 2. Schematic representation of typical cover distribution for the five cropping-surface management practices applied on the Greenmount and Greenwood sites (Sept.–June). Measured erosion index values are also shown for Greenmount.

techniques were used to produce a wide range of soil surface cover conditions.

The four stubble management practices applied after wheat harvest in late November were:

Bare fallow: Stubble burnt soon after harvest; weed control by tined cultivation.

Stubble incorporation: Disk cultivation to incorporate much of the stubble, followed by tined cultivation (usually one disk operation).

Stubble mulch:	Cultivation with 0·9 m sweep tines throughout the fallow to maintain maximum crop residue on the surface until near planting time.
Zero tillage:	Weed control by herbicides to maintain maximum stubble cover.

Under the summer crop treatment either sorghum, sunflowers or maize was planted during October–December. Residue from the summer crop was incorporated into the soil after harvest in March–June. Typical seasonal cover distribution for each treatment is shown in Fig. 2 along with the mean monthly erosion index (EI_{30}).

Experimental Design

Runoff and soil movement were monitored on five catchments at each location. Catchments are separated by broad-base contour banks with a 0·3% channel slope. Catchment characteristics are summarized in Table 3, and the layout of the Greenmount experiment is shown in Fig. 3. Trial design is similar at both sites. The distance between banks are standard (single spaced) at Greenwood and 'double spaced' at Greenmount (Table 3) (Soil Conservation Handbook, Department of Primary Industries, 1977).

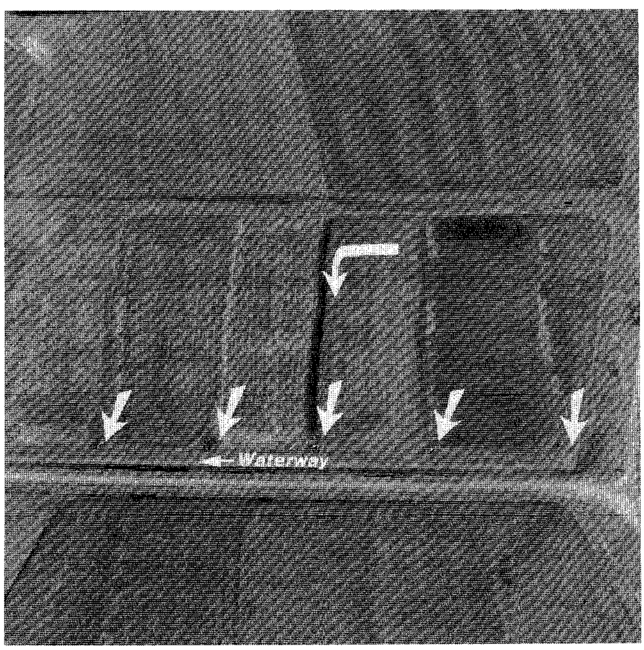

Fig. 3. Oblique aerial photograph of the Greenmount site showing the contour bay catchments. Arrows indicate water flow direction.

Contour bay catchments were chosen as a unit of study because:

- each bay can be considered a management unit and is therefore well suited to studying effects of different cultural treatments;
- such catchments have become a basic hydrologic and erosion unit with the widespread construction of contour banks in the grain growing areas;
- spatial variability of rainfall and soils between contour bays is small.

Treatments except summer crop and zero till in the first three years were rotated to different bays each year in order to minimize the possibility of catchment differences being interpreted as treatment effects. Residual effects of treatments were neglected, as:

(a) The final tillage operation and planting reduced stubble levels to less than 1 t ha^{-1} after planting.

(b) Quantities of stubble residues persisting beyond the life of the following crop were negligible compared with quantities (>5 t ha^{-1}) produced by that crop.

(c) Treatments produced gross differences in stubble levels immediately they were applied.

(d) Results from other research have shown that soil properties (CEC, organic carbon, total nitrogen and aggregate dispersion) would not be significantly altered during the experiment (Loch and Coughlan 1984).

Table 3. Summary of catchment characteristics at the Greenmount and Greenwood soil erosion experiments

Site		Greenmount	Greenwood
Soil type		Black earth	Grey clay
Parent material		Basalt	Walloon sandstone
Catchment area	(ha)	0·78–1·42 ha	0·72–1·00 ha
Slope	(%)	5–7	4–5
Slope length	(m)	56–61 m	35–40 m
Channel slope	(%)	0·3	0·3
Channel length	(m)	200	220

Measurements

Meteorology

Meteorological instruments consisted of a class A pan evaporimeter, paper wick atmometer, daily read rain gauge, Mort pluviometer, and a Casella thermo-hydrograph.

Hydrology and soil erosion

In order to determine the hydrology and soil movement within contour bay catchments, it was necessary to measure runoff, its sediment content, rill erosion and deposition of sediment in contour channels.

Surface runoff. Runoff was measured from each catchment as it discharged into a grassed waterway through either 0·61 m H flumes or 90° V-notch weirs. Water levels were recorded on Stevens Type F float recorders or locally manufactured float recorders.

Suspended sediment. Samples of runoff water were collected at the weir or flume for determination of suspended sediment. Samples were collected by a rising stage sediment sampler and in some catchments by an automatic sequential pumping sampler. Methods of calculating suspended loads are presented in detail by Freebairn and Wockner (1986).

Rill erosion. Rills were measured by field survey immediately after each erosion event. The depth and width of each rill was recorded at intervals of approximately 20 m. A map of the rilling pattern was recorded for each major event. Determining the volume of rilling was simplified since the depth of rills were uniform to the depth of cultivation, and rill cross-sections were nearly rectangular.

Sediment deposit fans. The volume of soil deposited in the contour channels was determined after each major erosion event. The depth and area of each fan was determined by walking through the wet fans and measuring depth of loose soil. Allowance was made for the depth of cultivated soil. When the catchments dried, cross-sections were cut through some fans to check the depth of cultivated and deposited soil against the above measures. Soil density of fans was measured on drying to convert measured volumes to masses.

This procedure was compared with two other methods:

(i) Change in channel cross-section was measured after a major event (5 February 1980) at Greenmount (Galletly, personal communication). The change in cross-section represented 92 t ha^{-1}, compared to 85 t ha^{-1} determined by fan volume.

(ii) Sheet steel plates (10 cm by 10 cm) attached to 20 mm diameter by 30 cm long rods were placed flush with the soil surface where sedimentation was expected (at the base of rill depressions and the ponding areas in front of weirs and flumes).

Soil movement determined using the plates was compared with the survey method in March 1984 (Lovell, personal communication), and measurements of 14 and 15 t ha^{-1} were obtained respectively.

Independent operator estimates of soil movement were in agreement, with 10% variation for losses less than 20 t ha^{-1}, and ± 10 t ha^{-1} for losses greater than 50 t ha^{-1}. Soil movement was estimated by the same two operators throughout the experiment.

In situ soil loss was also measured using steel pins. Pins (10 mm diameter by 40 cm long) were placed 25 cm into the soil to determine depth of soil removed due to rill and interrill erosion. They were found to be unsatisfactory due to need for replacement after cultivation and soil swelling.

Calculation of Total Soil Movement

Total soil movement is defined as the mass of soil that moves into or through the contour channel. That is, total soil movement equals deposition in fans plus total suspended load. The component deposited in fans is not lost from the paddock, but is removed from the cultivation and crop production plane and deposited in a channel. When the channel fills with sediment, it must be cleaned out to maintain the drainage and sediment trap network.

Measurement of total soil movement allows data from these experiments to be related to most plot erosion studies where net soil movement to the bottom of the slope is measured. Interrill erosion is almost impossible to determine directly from changes in soil level, due to soil swelling. The amount of interrill erosion was determined by subtracting rill volume from total soil movement. This analysis allowed the definition of sources and sinks of soil moving within the catchment. Volumes were converted to masses using measured bulk densities for fans and the cultivated layer.

Surface Cover

Projected cover

The proportion of the soil surface covered from vertical raindrop impact is referred to as projected cover. Cover was measured after each runoff event and after tillage operations. Vertical black and white photographs were taken at five locations in each bay using a 50 mm lens at a height of 2 m above the ground. A point quadrat method was used to determine the percentage of ground cover from the photographs (Laflen *et al.* 1978). In addition, visual estimates of surface cover were made from 1 m^2 quadrats at 20 random locations in each bay. It was found that the mean of visual estimates of cover was within 5% of the mean from photographic analysis for a wide range of conditions. The photographs serve as a permanent record of surface cover, orientation of stubble, and tilth.

Contact cover

Contact cover is the percentage of the soil surface which has stubble or crop in contact with the soil. It is distinguished from projected cover (Rose *et al.* 1983) on the basis that it is important in determining velocity of overland flow, whereas projected cover describes protection of the soil against raindrop impact. For fallows, projected cover and contact cover may be the same, but for growing crops the contact cover may be much smaller. Visual estimates of contact cover were made under growing crops.

Other Measurements

Soil moisture was measured gravimetrically at nine locations in each bay to a depth of 150 cm. Monthly samples were collected during 1976–78. Soil was sampled immediately after harvest, mid-fallow and just before planting for the period 1978–1984. Crop yield data were also measured.

Results and Discussion

Some effects of catchment moisture and cover conditions on runoff are presented, since runoff is the major factor contributing to soil movement. Annual soil movement is related to treatments and surface cover. Results from several events are presented to demonstrate effects of catchment moisture, cover, and rainfall intensity on erosion rates. A statistical model of erosion is derived.

Effect of Surface Cover on Runoff and Soil Movement

Runoff

Relationships between runoff and surface cover observed on the black earth and grey clay sites are presented for a range of catchment moisture conditions in Fig. 4. The qualitative description of these catchment conditions was based on antecedent rainfall, crop growth stage and nearest available soil moisture data.

When surface cover is present, high infiltration rates are maintained as cover absorbs raindrop energy, reducing aggregate disruption and surface sealing. Also the integrity of surface microrelief is maintained longer, thus preserving surface-water storage. Interflow rates may be higher when surface cover is present, thereby increasing time for free water to infiltrate (Boughton and Freebairn 1981). Once the soil profile is full, cover has little effect on total infiltration, as infiltration rates are then determined by the hydraulic conductivity of the whole profile, rather than surface restrictions. Infiltration rates for these wet clay soils may vary from 4 mm h^{-1} (Freebairn *et al.* 1984) to as low as 0·025 mm h^{-1} for ponded conditions (Swartz 1966).

Antecedent moisture is an important factor determining runoff, especially on cracking clay soils (Swartz 1966). This is demonstrated by the reduced runoff and soil loss occurring under sunflowers in 1980–81 relative to stubble retained conditions (Table 4). A sunflower crop, while often considered an 'erosion inducing' crop due to its poor cover charactersitics (maximum projected cover 60%, basal cover 5%), does provide better soil protection than bare fallow and maintains a soil moisture deficit for much of the summer period. Sorghum provides greater projected and basal cover than sunflowers, with consequent lower runoff and soil movement rates (Freebairn and Wockner 1984).

Marston (1978) found that for a black earth at Gunnedah, retention of stubble reduced peak runoff rates but generally did not reduce total runoff. However, in one high intensity (180 mm h^{-1}) storm there was a marked decrease in runoff volume and rate; all other storms had less than 46 mm h^{-1} peak rainfall rate. This suggests that a critical rainfall intensity is required before a response to surface cover becomes apparent, and this is consistent with results from this study. For example, prolonged low intensity rainfall (<20 mm h^{-1}) occurred at Greenmount on 1–2 May 1983 and 7–8 April 1984. The variation in per cent runoff between treatments was less than 11%, while the mean runoff for the two periods was 70

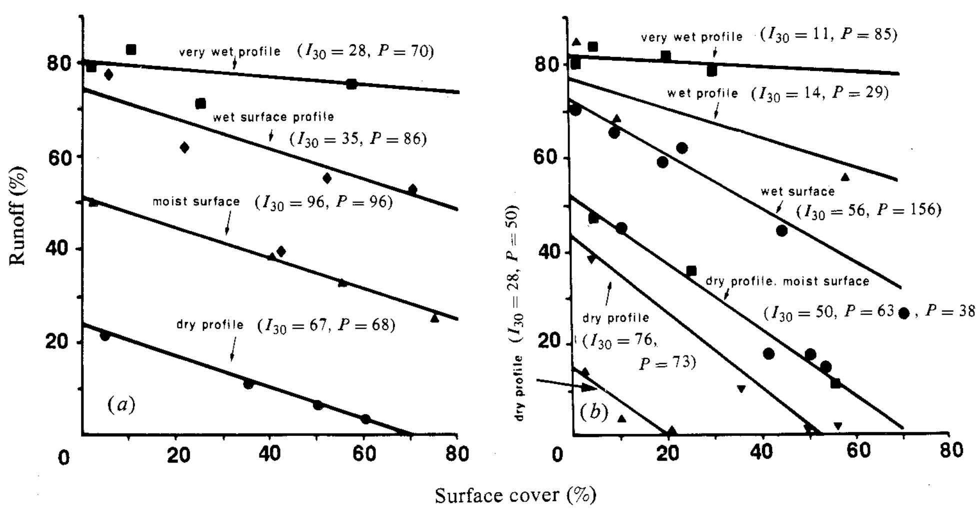

Fig. 4. Effect of surface cover on runoff for the Greenmount black earth: (*a*) and the Greenwood grey clay, (*b*) for selected storms under varying antecedent soil moisture conditions. The maximum 30 min rainfall intensity (I_{30} mm h^{-1}) and rainfall (*P*, mm) for each storm are in brackets.

mm and 40 mm respectively. Daily runoff for different stubble management strategies has been successfully predicted using a water balance model (Freebairn and Boughton 1985). This model did not explicitly consider rainfall intensity, indicating that antecedent moisture and cover are the most important factors determining infiltration.

Annual Soil Movement

Annual runoff and soil movement for the Greenmount and Greenwood sites are summarized in Tables 4 and 5 respectively. The surface cover conditions throughout the storm period (October–March) are included. Increasing surface cover reduced annual runoff and to a greater extent the mean sediment concentration of the runoff (Fig. 5).

Reductions in total runoff are associated with reduced runoff rates (Freebairn and Boughton 1985), runoff velocity (Meyer *et al.* 1970), and hence the stream power (Bagnold 1977) available for transport of sediment. Surface cover also reduces the amount of soil exposed to detachment and disruption by raindrop impact, providing less soil for transport. The maintenance of surface microrelief

Table 4. Summary of summer cover, annual runoff and soil movement on a black earth at Greenmount 1976–84

Treatment	Units	Bare fallow	Stubble incorporated	Stubble mulch	Zero tillage	Summer crop
1976–77						Sorghum
Cover	%	< 10	20–10[B]	—	—	0–60
Runoff	mm	34·2	12·8	—	—	57·8
Soil movement	t ha^{-1}	20 (1)[A]	2 (1)	—	—	60 (5)
1977–78						Sorghum
Cover	%	5	40–10	—	—	0–70
Runoff	mm	0·3	0	—	—	0·8
Soil movement	t ha^{-1}	0	0	—	—	0
1978–79						Sorghum
Cover	%	15–5	60–35	65–50	90–80	25–60
Runoff	mm	31·0	8·6	5·3	5[C]	4·2
Soil movement	t ha^{-1}	34 (2)	6 (1)	1 (1)	negl.	negl.
1979–80						Sorghum
Cover	%	2	40–10	62–20	90	5–80
Runoff	mm	62·8	34·9	29·9	20·7	13·8
Soil movement	t ha^{-1}	124 (3)	5 (1)	2 (1)	negl.	1 (1)
1980–81						Sunflower
Cover	%	5	20–10	40–20	70	10–50
Runoff	mm	129·4	112·8	64·8	97·4	77·5
Soil movement	t ha^{-1}	91 (3)	66 (3)	12 (2)	4 (2)	34 (3)
1981–82						Sunflower
Cover	%	5	80–20	80–40	75–70	5–30
Runoff	mm	84·7	54·1	46·0	79·8	64·4
Soil movement	t ha^{-1}	29 (5)	1·2 (1)	1·1 (1)	1·1 (1)	89 (4)
1982–83						Sorghum
Cover	%	5	45–10	60–15	90–50	10–30
Runoff	mm	125·6	127·9	137·6	155·6	116·9
Soil movement	t ha^{-1}	68 (2)	29 (2)	15 (2)	7 (2)	9 (3)
1983–84						Maize
Cover	%	2	20–10	40–25	70–60	50–90
Runofff	mm	71·0	44·1	63·7	74·6	48·7
Soil movement	t ha^{-1}	20 (3)	0·4 (2)	0·4 (2)	0·7 (1)	0·1 (1)
Mean 1978–84						
Runoff	mm	88·6	63·7	57·9	72·2	54·2
Soil movement	t ha^{-1}	61·0	17·9	5·3	2·1	22·3

[A] Figures in brackets indicate number of events contributing to soil movement.
[B] Projected cover range for treatment application (Nov.-Dec.) to April or October-April for summer crop.
[C] Estimated from peak discharge and soil mosture data.

through reduced raindrop impact, and the increased tortuosity of flow due to contact cover, leads to less runoff, lower concentrations of sediment in runoff water and therefore large reductions in total sediment loads.

Retention of stubble, either incorporated into the soil or left on the surface as a mulch, reduced soil movement by greater than 70% compared to bare fallow. Whereas stubble mulch was the more effective cultivated fallow practice in reducing soil erosion, the growing of a summer crop provided effective soil protection once the crop was established. A summer cropping phase often results in little ground cover early in the summer period, but the growing crop creates increased cover and soil moisture deficit.

Table 5. Summary of summer cover, annual runoff and soil movement on a grey clay at Greenwood 1978–84

Treatment	Units	Bare fallow	Stubble incorporated	Stubble mulch	Zero tillage	Summer crop
1978–79						Sorghum
Cover	%	3	45–20[B]	60–30	70	0–30
Runoff	mm	16·7	2·6	0·8	0[C]	7·9
Soil movement	t ha^{-1}	4 (1)[A]	0	0	0	2 (1)
1979–80						Sorghum
Cover	%	2	50–25	70–40	70–60	10–50
Runoff	mm	45·7	21·8	6·7	0[C]	10·9
Soil movement	t ha^{-1}	49 (2)	5 (1)	1 (1)	0	1 (1)
1980–81						Sunflower
Cover	%	2	35–8	50–15	56–25	5–40
Runoff	mm	170·8	155·2	123·9	145·6	125·2
Soil movement	t ha^{-1}	111 (5)	31 (3)	16 (3)	10 (3)	51 (3)
1981–82						Sunflower
Cover	%	5	25–40	40–50	56	10–35
Runoff	mm	21·5	6·5	5·4	12·2	49·1
Soil movement	t ha^{-1}	5 (1)	0·3 (1)	0·2 (1)	0·2 (1)	32 (1)
1982–83						Sorghum
Cover	%	5–2	26–3	42–5	54–30	23–40
Runoff	mm	143·7	115·0	135·5	115·4	119·5
Soil movement	t ha^{-1}	11·7 (3)	7·2 (2)	6·1 (2)	0·3 (1)	30·3 (2)
1983–84						Sorghum
Cover	%	2	30–13	45–36	62	10–70
Runoff	mm	40·8	46·5	36·7	53·0	27·7
Soil movement	t ha^{-1}	9·2 (2)	3·2 (2)	0·1 (1)	0·2 (1)	0·4 (2)
Mean 1978–84						
Runoff	mm	73·2	57·9	51·5	54·4	56·7
Soil movement	t ha^{-1}	31·6	7·8	3·9	1·8	19·8

[A] Figures in brackets indicate number of events contributing to soil movement.
[B] Projected cover range for treatment application (Nov.–Dec.) to April or October–April for summer crop.
[C] Estimated — no water in channel.

The most effective management system for reducing soil erosion was zero tillage. Under zero tillage, stubble cover is maximized and soil disturbance is minimized. It is difficult to determine the effect of cultivation *per se* on sediment loads, but it appears that cover is the major factor determining runoff, sediment concentration and consequent soil movement.

A feature of soil erosion in Queensland is that there are relatively few storms resulting in runoff and subsequent soil movement each summer period. At both sites, more than 50% of the total soil movement over 6–8 years of observation resulted from two major rainfall events. Edwards (1980) found similar patterns of erosion at Wagga and Gunnedah NSW.

Owing to the episodic nature of soil erosion in Australia, extrapolation of data from single events, to generate long-term statistics, presents a methodological problem. However, while the data presented cover only six and eight years of experimentation at two sites, the wide range of storm types experienced gives confidence to the generality in time of the results obtained (Freebairn and Boughton 1985).

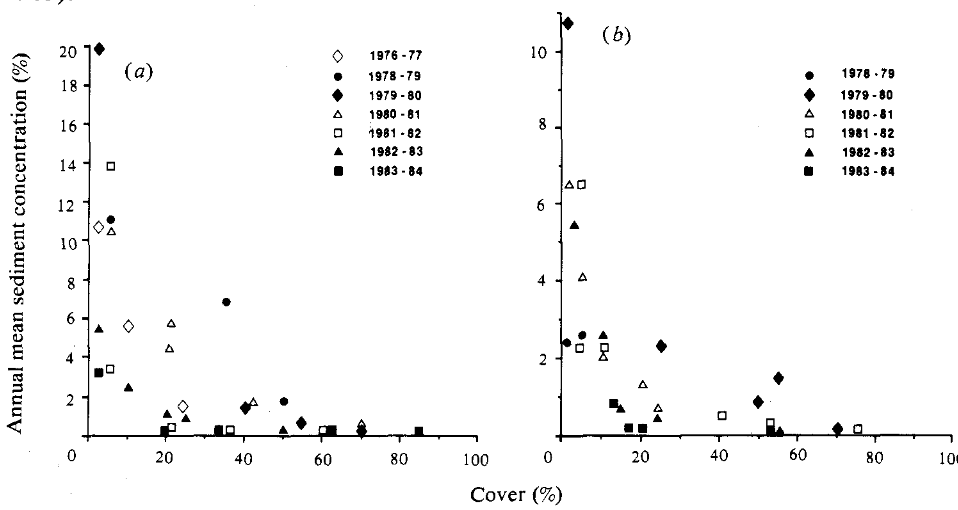

Fig. 5. Annual mean sediment concentration of runoff entering the contour channel *v.* cover for Greenmount (*a*) and Greenwood (*b*) 1976–84.

Analysis of Single Events

Runoff and soil movement resulting from two contrasting storm types are presented for the two soil types studied (Fig. 6). The events presented for the black earth represent a high intensity storm (I_{15}, maximum 15 min rainfall intensity = 131 mm h^{-1}), on a dry catchment (Fig. 6*a*) and prolonged lower intensity rain (I_{15} = 56 mm h^{-1}) on a wet catchment (Fig. 6*b*). The two events presented for the grey clay represent a moderate intensity storm (I_{15} = 59 mm h^{-1}) on a dry catchment (Fig. 6*c*) and a high intensity storm (I_{15} = 91 mm h^{-1}) followed by prolonged lower intensity rainfall (I_{15} = 30 mm h^{-1}) on a wet catchment (Fig. 6*d*).

The extreme rainfall event on 5 February 1986 at Greenmount resulted in 99 t ha^{-1} soil movement on bare fallow compared with 2 t ha^{-1} soil movement on the catchment with 55% soil cover. Runoff and peak runoff rate were also reduced (45 mm and 55 mm h^{-1} cf 30 mm and 17 mm h^{-1}) (Fig. 6*a*). The prolonged lower intensity event on 7 February 1981 at Greenmount (Fig. 6*b*) resulted in high volumes of runoff from all surface conditions with soil movement reduced by surface cover. Similar results were obtained on the Greenwood grey clay (Fig. 6*c*, *d*). Total runoff from individual events is mainly a function of antecedent moisture and rainfall and to a lesser extent cover, whereas soil loss is determined by cover and consequent runoff intensity.

Runoff from zero tillage was slightly greater than from the stubble mulched treatment on wet catchments, yet more soil movement occurred on the latter. This may be due to the greater stability or the higher cover on the non-tilled surface. Observations showed that overland flow did not concentrate as much where the surface had not been tilled, resulting in more uniform flow with lower velocity. Each row of residual crop stubble acted as a 'mini-terrace', slowing and thus spreading overland flow.

High intensity storms present the greatest hazard to maintenance of contour banks and waterways. The Greenmount storm on 5 February 1980 was classed as having a greater than 100-year return period (Queensland Soil Conservation Handbook 1977). Estimated soil losses of up to 400 t ha^{-1} on bare fallow were recorded nearby (Marshall *et al.* 1980) when a high proportion of soil conservation structures failed. Failure of contour banks was often a result of deposited sediment blocking channel flow. The effectiveness of surface cover in reducing soil loss and subsequent structural failure is highlighted by these results.

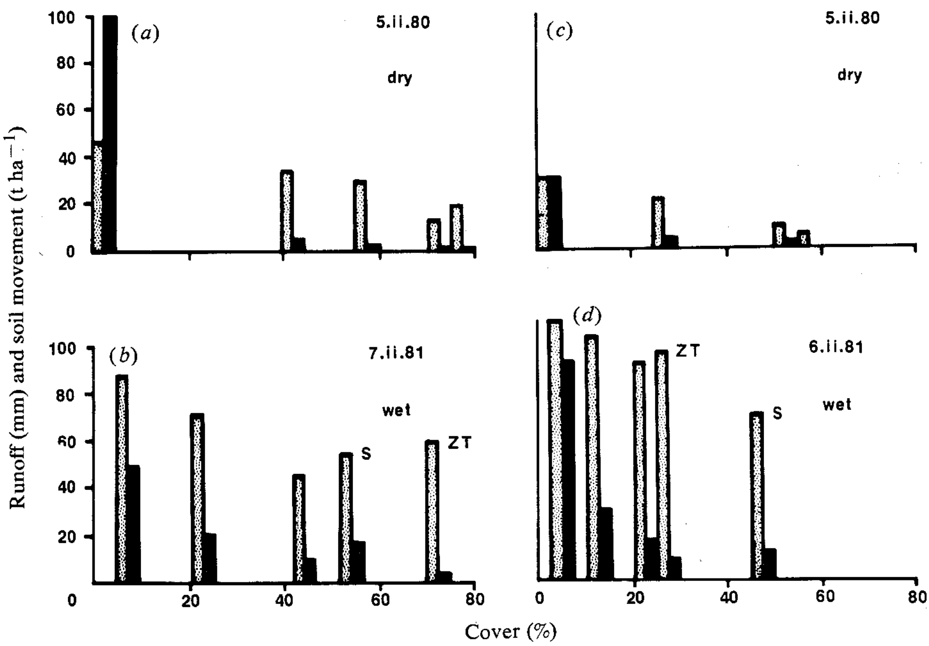

Fig. 6. Runoff (shaded bar), soil movement (solid bar), and projected cover for two storms at Greenmount (*a*, *b*) and Greenwood (*c*, *d*). The date and prior water content of catchments are included for each event. S refers to sunflowers which had a basal cover of 5–10%, ZT refers to zero tilled catchments. (*a*) P = 92 mm. I_{15} = 131 mm h^{-1}; (*b*) P = 114 mm, I_{15} = 56 mm h^{-1}; (*c*) P = 62 mm, I_{15} = 59 mm h^{-1}; (*d*) P = 156 mm; I_{15} = 91 mm h^{-1}.

Statistical Model of Single Event Soil Movement

In an attempt to determine the major measurable variables controlling soil movement, a multiple regression approach was adopted. Total event runoff, peak runoff rate, rainfall intensity (I_{15}), erosion index (EI), cover, squared terms and interactions of these variables were assessed on the basis of the amount of variance (R^2) that could be accounted for by a range of multiple regression models. Data from every event where sediment data were collected were used in the analysis.

Correlation coefficients for linear and quadratic relationships between parameters and soil movement are presented in Table 6. Peak runoff is the most strongly correlated, followed by runoff depth, erosion index, rainfall intensity, and cover. The population of data is likely to be biased towards low cover and high intensity events. Measurable runoff, soil movement, and sediment loss have rarely

Table 6. Correlation coefficients for soil movement and several catchment, rainfall and flow parameters

Parameter	Greenmount	Greenwood
Peak runoff	0·7291	0·6877
(Peak runoff)^2	0·7788	0·8141
Runoff depth	0·4605	0·5403
(Runoff depth)^2	0·4285	0·6244
Erosion index	0·3996	0·5742
(Erosion index)^2	0·3356	0·5845
I_{15}	0·3504	0·4604
$(I_{15})^2$	0·3235	0·5153
Cover (projected)	−0·3239	−0·2269
(Cover)^2	−0·2574	0·1933

been recorded for high cover, low intensity events. This analysis gives some insight into the important parameters influencing soil erosion in these catchments. The following models were selected on the basis of highest r^2 values with only two independent parameters. Inclusion of an extra term explained less than 4% of the variance, and this was not considered useful. All parameters in the regression equations were significant at the 1% level.

The derived models were:

Greenmount

$$M_s = 1{\cdot}392Q_p - 0{\cdot}0183(C \times Q_p) - 2{\cdot}36 \tag{1}$$
$$(\text{number of events} = 82;\ r^2 = 0{\cdot}87),$$

where M_s = soil movement (t ha^{-1})
Q_p = peak runoff rate (mm h^{-1})
C = cover (%).

Greenwood

$$M_s = 0{\cdot}022Q_p^{\,2} - 0{\cdot}014(C \times Q_p) + 1{\cdot}16 \tag{2}$$
$$(\text{number of events} = 75;\ r^2 = 0{\cdot}76).$$

The graphical form of these equations is presented in Figs 7 and 8. This statistical analysis indicates that peak runoff rate and the interaction of peak runoff with cover are the major factors determining soil movement at these sites. Peak runoff is an index of the runoff velocity or available stream power (Bagnold 1977). Projected cover is a direct measure of the proportion of the surface which is protected from raindrop energy and overland flow energy. Contact cover increases the tortuosity of water. Equations (1) and (2) could be used to predict soil movement, but the major problems in using these models are: (*a*) the questionable generality of the models; and (*b*) the difficulty in predicting peak runoff rate which is dependent on runoff, catchment characteristics and rainfall intensity.

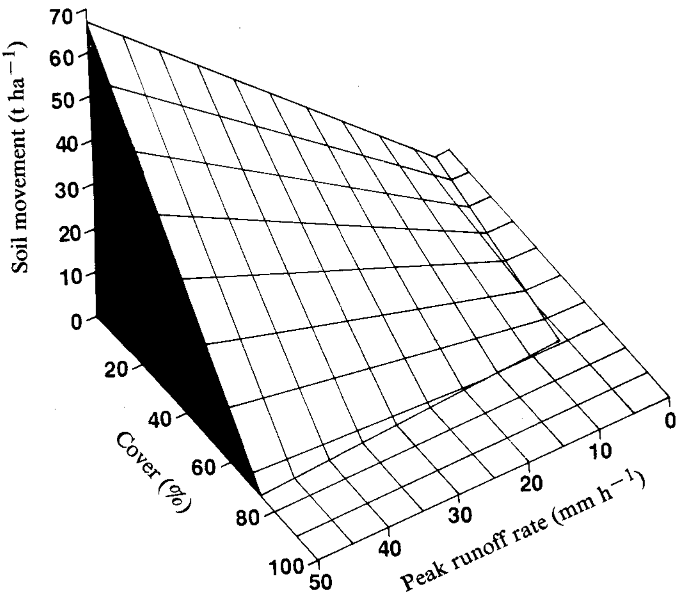

Fig. 7. Three-dimensional representation of the relationship between soil movement, cover and peak runoff rate (from equation 1) for the Greenmount site.

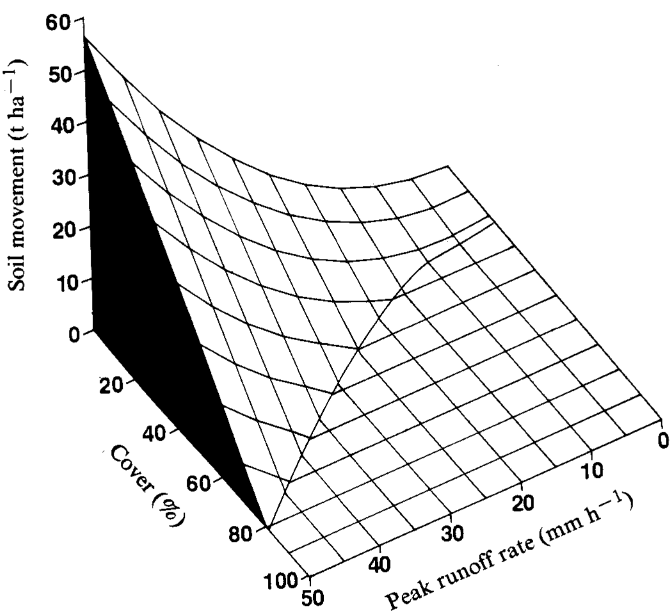

Fig. 8. Three-dimensional representation of the relationship between soil movement, cover and peak runoff rate (from equation 2) for the Greenwood site.

Sources of Eroded Soil

An analysis of the sources and sinks of eroded material was carried out to determine the relative importance of rill and interrill erosion. An understanding of the source of eroded soil may elucidate some of the processes of erosion and could have implications for the 'quality' of eroded soil and the consequences of erosion. Where soil is lost by 'sheet' erosion, relatively rapid nutrient loss will occur,

Table 7. Sources and sinks of transported soil-Greenmount black earth 1986–84
Ng, Negligible; ND, Not determined; DD, Difficult to define — poorly defined rills or fans

Date	Runoff (mm)	Cover (%)	Channel deposit (t ha^{-1})	Suspended sediment (t ha^{-1})	Rill (t ha^{-1})	Interrill (t ha^{-1})	Total soil movement (t ha^{-1})
31.x.76	14·6	8	15	ND	0·7	15	15
	26·8	2	34	ND	8	28	36
9.xi.76	5·0	5	34	ND	ND	ND	34
14.xi.76	5·0	12	3	ND	ND	ND	3
	9·6	5	8	ND	ND	ND	8
16.i.77	13·3	5	4	ND	ND	ND	4
29.xii.78	6·9	10	4	0·41	ND	ND	4
15.iii.78	15·3	5	25	4·38	ND	ND	29
	7·7	35	6	0·84	ND	ND	7
21.xii.79	0[A]	2	4·6	0	0·6	4·0	5
27.i.80	16·7	2	18	2·58	7	13·6	21
5.ii.80	45·4	2	85	13·80	3·8	95	99
	34·9	40	3	1·85	Ng	4·8	5
	29·9	55	1	0·85	Ng	2	2
5.ii.81	23·6	21	33	3·14	7	29	36
	25·6	5	33	3·40	16·6	19	36
7.ii.81	71·6	21	14	4·68	5	15	20
	55·2	52(5)[B]	15·2	1·60	DD	Ng	17
	45·2	42	5	2·12	9	2	11
	88·8	5	44	6·99	12	39	51
4.iv.81	7·7	4	4	0·18	2·3	1·9	4
20.iv.81	10·2	5	12·5	3·93	1	15	16
3.xii.81	46·3	5	74	6·70	24	56	81
	28·9	80	0·7	1·27	0	2	2
20.xii.81	2·7	30(5)	2·9	0·39	Ng	3	3
23.xii.81	4·5	35(6)	3·5	0·45	Ng	3·9	4
4.iii.82	10·7	5	4·7	0·16	2·5	2·4	5
31.x.82	2·7	10	2·7	0·87	Ng	3·5	3
2.v.83	57·1	10	25	2·38	25	2	27
	55·8	2	50	7·32	45	12	57
	44·2	29	3	0·74	4	1	5
	52·5	57	3·5	0·99	3	2	5
	50·1	25	9	1·68	10	2	12
21.vi.83	52·9	5	0·6	0·13	1·4	0·6	2
	72·4	2	9·3	1·11	5·7	5·3	11
	65·0	30	DD	0·50	1·3	0·7	2
	67·4	10	1·9	0·52	2·1	0·9	3
9.iii.84	6·1	2	14·6	1·52	DD	≈10	16
8.iv.84	42·9	2	3·2	0·40	3·2	Ng	4
Total	—	—	618	78	190	390	705

[A] All runoff absorbed in cracks in channel.
[B] Value in brackets is contact cover, if no brackets projected and basal cover were equal.

especially where the nutrient profile is steep and/or the erosion process is selective. For a soil which predominantly rills, erosion is obvious and therefore some ameliorative action may be taken.

A summary of soil movement patterns for both experiment sites is presented (Tables 7 and 8) for all events where greater than 2 t ha^{-1} soil movement was recorded.

Soil movement on the grey clay (Greenwood) site was dominated by rainflow or interrill erosion which accounted for 82% of soil movement for the events studied. On this site it has consistently been observed that overland flow is characterized by sheet flow, rather than concentrated flow along rills. When rills do form, they quickly stabilize. For example, the event on 27 January 1980 resulted in moderate rill erosion (3·5 t ha^{-1}), but a subsequent larger runoff event (5 November 1980)

Table 8. Sources and sinks of transported soil — Greenwood 1978–84

Date	Runoff (mm)	Cover (%)	Channel deposit (t ha^{-1})	Suspended sediment (t ha^{-1})	Rill (t ha^{-1})	Interrill (t ha^{-1})	Total soil movement (t ha^{-1})
27.i.80	13·8	5	15	2·1	3·5	13·5	17
5.ii.80	29·3	5	27	3·1	1	29	30
	21·8	25	4	1·04	ND	ND	4
	10·6	50	4·5	0·26	ND	ND	5
25.xi.80	8·4	2	7	1·17	2	6·2	8
	28·2	5	30	4·68	ND	ND	35
6.xii.80	4·5	2	3	0·42	Ng	ND	3
	3·6	10	2·5	0·27	Ng	ND	3
5.ii.81	7·1	2	1·5	0·56	Ng	ND	2
6–8.ii.81	121·1	24	2·4	6·54	Ng	8·9	9
	137·6	2	75	20·85	8	87·9	96
	117·3	20	11	5·40	5	11·4	16
	93·3	45(5)[A]	10	2·18	Ng	12·1	12
	131·9	10	20	10·26	5	25·3	30
3.xii.81	7·1	10(2)	4	1·08	4	1	5
24.xii.81	17·2	10	3	1·96	Ng	10	5
	23·7	30(5)	24·4	1·62	Ng	26	26
3.xii.82	11·6	26	1·7	1·01	Ng	ND	3
	16·1	23	25	1·51	DD	30	30
	13·0	5	5	0·96	Ng	0·5	6
27.v.83	11·7	6	3·7	0·01	5·2	Ng	5
	8·2	4	2·0	0·02	4·2	Ng	4
	6·5	2	2·9	0·01	5·5	Ng	5
21.vi.83	70·9	5	1·1	0·98	1·4	0·7	2
9.iii.84	11·2	2	8·0	0·86	2·9	6	9
Total	—	—	294	69	48	268	370

[A] All runoff absorbed in cracks in channel.

increased rill volume by only 1 t ha^{-1}. The depths and peak rates of runoff were greater during the second event (13·8 mm and 18·6 mm h^{-1}, cf. 29·3 mm and 44·7 mm h^{-1}), and total soil movement was nearly doubled (17 t ha^{-1} cf 30 t ha^{-1}).

Rill erosion was more important on the black earth (Greenmount), but was still the minor source, accounting for only 33% of soil movement. During one major event (5 February 1980) soil movement was 99 t ha^{-1}, of which only 4% resulted in rilling. Rills formed in a prior event (27 January 1980) increased in size marginally. High intensity rainfall (150 mm h^{-1} for 20 min) effectively 'flooded' any rills present. Overland flow was observed as being almost completely sheet flow, with the whole plane covered with flowing water in the peak of the storm. Moss *et al.* (1979) found that high intensity rain disrupted the formation of channel flow and promoted sheet flow.

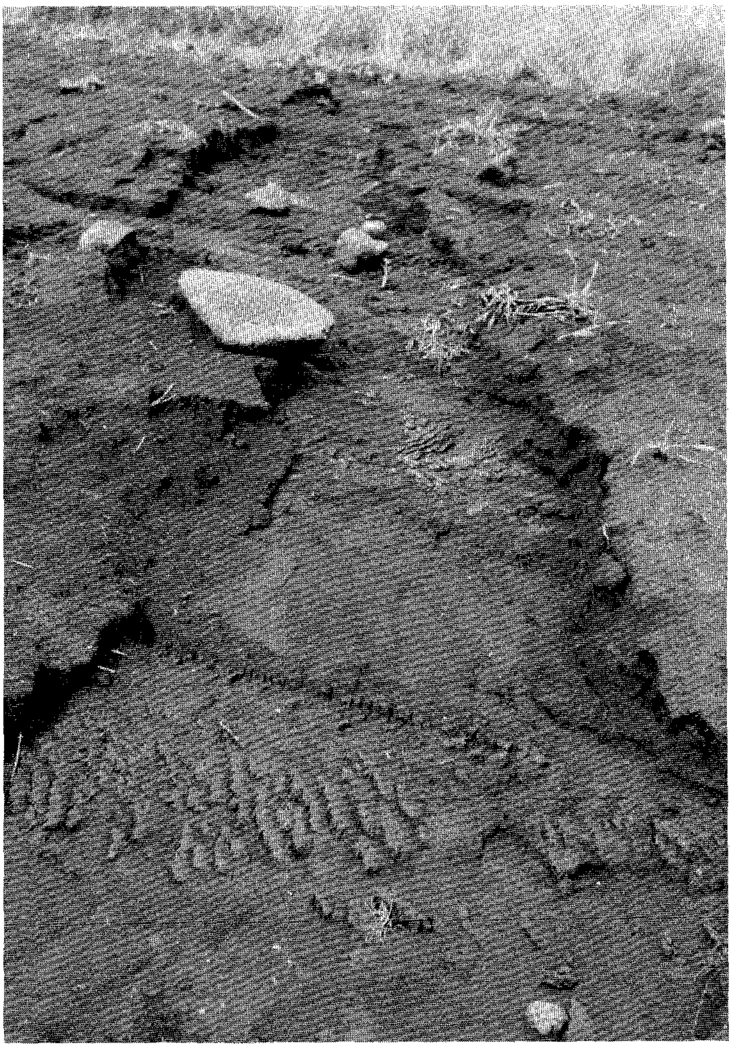

Fig. 9. A rill on the black earth showing the rectangular cross section of rills common on cultivated soils. The shear marks resulting from cultivation are visible along the base of the rill.

In a contrasting event (Greenmount, 2 May 1983), rills contributed 79% of the eroded soil. On this occasion prolonged low intensity rainfall (70 mm over 12 h, $I_{30} = 28$ mm h^{-1}) produced steadily increasing rates of runoff, similar to the rainfall rate, in highly channelized flow. Under these circumstances, the relatively high runoff rate (36 mm h^{-1}) which is usually recorded only in intense (>80 mm h^{-1}) storms, resulted in rills being the dominant source of eroded soil.

Rills on the black earth were distinct, with rectangular cross-section, the base of the rill generally being the bottom of the plough layer at 0·1 m depth (Fig. 9). Rills in zero till catchments, though less frequent (60–80 m apart compared to 10–20 m on bare catchments), were commonly deeper than 0·1 m, with V-shaped sections. Sediment fans in all treatments were discrete, with clear distinction between *in situ* and eroded soil (Fig. 10).

The shape of rills appears to be determined by the relative availability of detachable soil. The cultivated layer has less strength than the consolidated soil beneath. Therefore once rills form, any increase in rill capacity is achieved by undercutting of rill sides. In zero till surfaces where no ploughed layer exists, the relatively clean water reaching flow lines cuts the base of the rill, thus deepening rather than widening the channel.

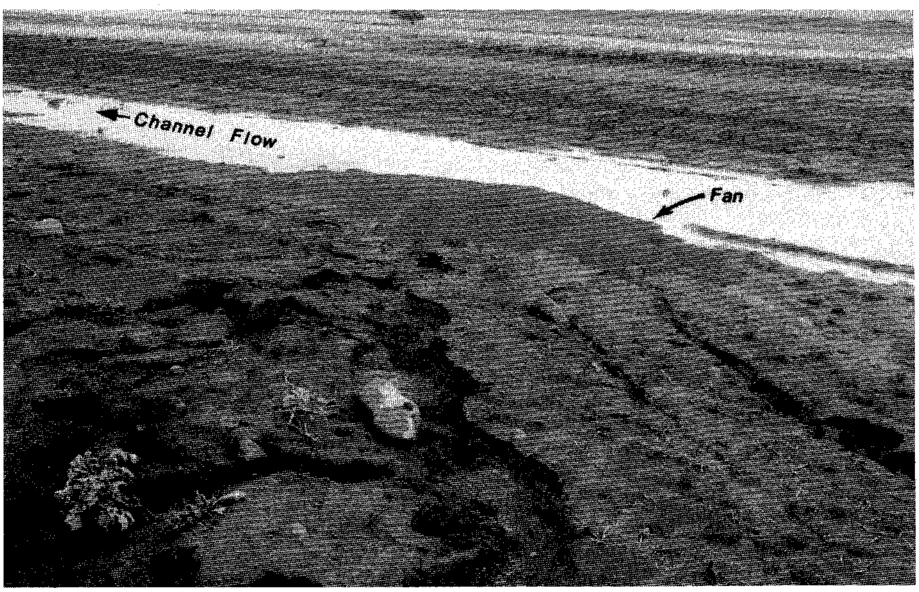

Fig. 10. A rill and associated sediment deposit on a black earth. The sediment fan is quite distinct from the *in situ* soil.

Measurement of sediment deposits on the grey clay was difficult, because rills and associated fans of eroded material in the contour channel were less defined. Differences in deposition patterns may be related to the way soil aggregates break down under rainfall. The black earth is well aggregated with a bimodal size distribution. The grey clay tends to slake, and so is transported as finer particles (Fig. 11) and has less well defined fans.

It is useful to differentiate between sources of eroded soil. The relative importance of the source of soil, or the set of processes detaching and transporting soil, could influence the methods of measurement used in an erosion study. For example, if rill erosion were the dominant source of material, estimates of rill volume alone would provide reasonable estimates of total soil movement. On the other hand, if interrill erosion is the main main source, detailed measurement of sediment deposits and suspended sediment would be necessary to estimate soil movement. It is almost impossible to determine the magnitude of interrill erosion by measuring changes in surface elevation on swelling soils.

While it can be concluded that interrill erosion was dominant for the conditions studied, caution should be exercised in transferring these findings to other scales of study, or other soil types, as the relative importance of detachment and transport mechanisms may change.

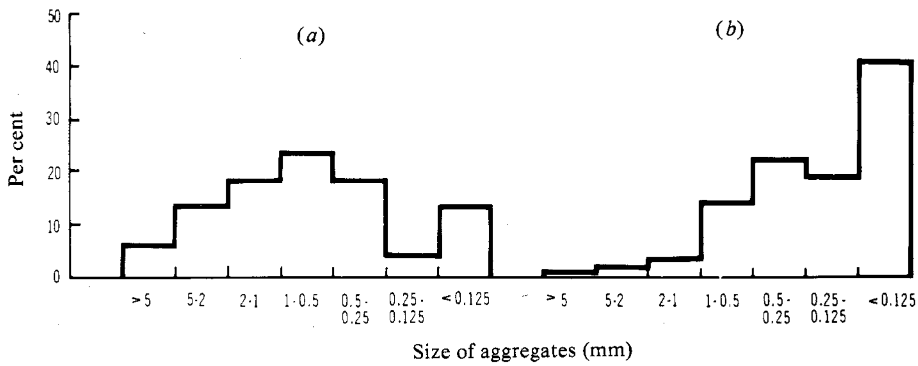

Fig. 11. Aggregate size distribution of soil transported in a rill on the black earth (*a*) and grey clay (*b*). Determined by wet sieving of samples collected 3.xii.81.

Particle Size Analysis of Eroded Soil

Particle size analysis of *in situ* and eroded soil (sediment fans and suspended sediment) was determined to show whether soil aggregates were broken down into ultimate particles and whether preferential transport of these particles was occurring.

Samples of *in situ*, erosion fan, and suspended sediment, were analysed for ultimate particle size distribution (Fig. 12). There is little change in the size distribution of the black earth from *in situ* to erosion fan. This highly aggregated

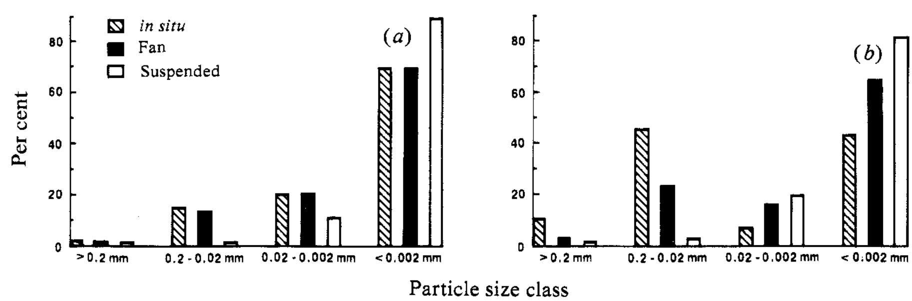

Fig. 12. Ultimate particle size analysis of *in situ*, erosion fan (contour channel) and suspended material (stage sediment sample) for Greenmount and Greenwood soils.

soil is transported *en masse* with negligible separation into ultimate particles. However, there is a 20% enrichment of the clay fraction in suspended material. This suggests that the finer material produced by aggregate disruption is preferentially transported out of the paddock, with the coarser sediment remaining in the channel.

The grey clay soil breaks down more than the black earth (Fig. 11) with resultant separation of particle sizes along the flow path (Fig. 12). Coarse and fine sand are progressively left behind, and suspended sediment becomes enriched in clay and to a lesser extent silt size particles. A consequence of this separation of ultimate particles is that nutrients or pollutants attached to clay are likely to be preferentially transported out of catchments.

Comparison of the Black Earth and Grey Clay Soils

Hydrology

Runoff from the two soils is similar, with 16% of October–March rainfall being lost from bare summer fallow and 11% from stubble mulch fallow on both sites. The mean annual rainfall over the 6-year period used for this comparison was 110 mm higher at Greenmount, whereas evaporative conditions were the same at both sites. This indicates that the black earth was able to accommodate the extra rainfall with only 16 mm additional runoff. This is reflected in the higher water storage capacity of the black earth (Table 1).

Compared to a bare fallow, a stubble mulch reduced runoff by 35% and 30% for the black earth and grey clay respectively. This reduction was reflected in increased storage of water in the soil and in some seasons resulted in improved grain yields.

Soil erosion

Although annual runoff depths are similar for both soils, the sediment concentration of water reaching the contour channel and total soil movement were twice as high at Greenmount.

The USLE (Wischmeier and Smith 1978) can be used to relate soil loss from different studies. The LS factor (slope and slope length) for Greenmount and Greenwood are 1·1 and 0·55 respectively. This twofold difference corresponds to the difference in mean annual soil movement for the bare fallow catchments. It seems reasonable to assume that the mean erodibilities (i.e. K factor of the USLE) of the two soils are similar. The K factor includes both infiltration, detachment and transport components, even if only implicitly. Both sites also have similar total runoff, and sediment concentrations, if the difference in LS factor is considered.

Implications for Agricultural Management

High erosion rates measured within contour banks indicate that establishment of contour or graded banks alone are insufficient to stabilize the soil under erosive rainfall. Experience shows that farmers can manage the amount of crop residue retained on the soil surface by their choice of implements, and frequency of cultivation. Results presented (Tables 4 and 5; Figs 5 and 6) show that soil movement is reduced by 80–90% if soil cover levels of 20–30% are maintained during the erosive period (October to March inclusive). Dickey *et al.* (1984) found a similar 'critical' surface cover level of 20% was effective in reducing erosion by at least 50% compared to bare mouldboarded soil. These levels of stubble are achievable with currently available equipment and stubble production levels obtainable on the Darling Downs. Crops such as sunflowers produce little surface cover. When grown in a rotation with residue from the previous cereal crop, runoff and erosion rates are reduced (Freebairn and Wockner 1984). Farming practices that maintain surface residue and a soil moisture deficit result in reduced runoff, lower sediment concentrations in runoff water, and dramatically reduced soil movement.

Zero tillage is the best management practice available for conserving soil, yet some problems exist in its use. Although erosion rates under zero tillage were less than 2 t ha^{-1} $year^{-1}$, soil erosion occurred as deep rills. This observation indicates that some cultivation is necessary after major runoff events, to fill in rills. Higher total runoff depths may result in lower moisture storage in some seasons.

Recommendations for Further Research

Runoff rate per unit width for any given soil condition is dependent on slope length. This study has shown that soil movement is strongly influenced by runoff rate. Foster (1982) showed a wide response of erosion to slope length for different soils, indicating a lack of 'universality' in the USLE relationship. Therefore, the effect of slope length on soil movement needs to be better understood for a range of slopes and soil types. The response of erosion to degree of slope is also highly variable (Foster 1982). While slope is not easily manipulated by man, it is desirable to know the influence of slope on erosion, so that appropriate slope limits can be set for cultivation.

Soil conservation structures are generally designed to withstand a certain return period event (e.g. 1:10 years, 1:50 years). The most severe events recorded at both sites of this experiment resulted in widespread failure of contour banks in the adjoining areas. Once breached, the contour banks failed to perform the function of runoff control and slope length reduction, and often acted to concentrate water to form gullies. This result suggests that the concept of designing soil conservation structures for short return periods (e.g. 1:10 years), when much larger events move most of the soil, requires re-examination if soil conservation designs are to be truly effective.

Vital to the prediction of soil erosion is the ability to predict runoff. Therefore, further research is required to characterize the hydrologic response of soils to climate and management.

Physically based models should be used to integrate the many processes involved in crop production. With water balance as the central theme, runoff, soil erosion, and crop production can be integrated to provide probabilistic data for specified systems. This approach offers one avenue for determining what erosion rates might be considered 'acceptable' in the longer term.

Conclusions

The highly aggregated clay soils of the Darling Downs break down to varying degrees when exposed to high energy rainfall. The detached and disrupted smaller aggregates and ultimate particles block continuous pores of the soil matrix, reducing infiltration rates and surface microrelief. When infiltration capacity of the soil is reduced, either by surface sealing or by natural reduction of permeability as the soil wets, high intensity rainfall becomes an important soil detachment and transport mechanism.

Cover, either in the form of a growing crop or crop residue, acts by reducing raindrop impact, thus maintaining infiltration rates. The associated reduction in the quantity of detached soil, and in runoff volume and velocity, leads to reduction in supply and transport of soil downslope. As a result where 20–30% of the soil surface is covered, soil erosion is dramatically reduced.

When the still highly aggregated eroded soil reaches a contour bank channel of 0·3% slope, only the suspended fraction of sediment is transported in the channel flow and the remaining 80–90% is deposited.

Patterns of erosion vary from storm to storm. In extreme events, rainfall intensity may be so high that channelized flow does not occur, possibly owing to helical flow being disrupted by raindrops (Moss *et al.* 1974) and 'flooding' of flow lines by high discharge volumes. In these situations soil is removed from the whole plane as sheet transport, the process being referred to as interrill erosion. For smaller events, flow may be highly channelized and stream power is concentrated along a small section of the plane, leading to the formation of the rills — termed rill erosion. In this study, the majority of soil erosion occurred in a few extreme events, and interrill erosion was the dominant source of erosion. Rills often appeared to be the major source of eroded soil in smaller events.

The application of conservation tillage (stubble retention) practices in conjunction with conservation structures will reduce the incidence of structure failure while dramatically reducing soil movement. Reduced runoff and soil movement will result in increased short-term yield and the maintenance of long-term productivity.

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