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The Effect of Furrow Length on Rain and Irrigation-induced Erosion on a Vertisol in Australia

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Abstract

Runoff and sediment movement were measured from irrigated furrows of different lengths on a Vertisol in central Queensland. Two farm properties (Denaro's and Roberts') were used to compare a short furrow length (SFL) and a long furrow length (LFL). At Denaro's farm, furrows were 241 and 482 m long, and at Roberts' farm they were 151 and 298 m long, with gradients of 1·0% and 1·3% respectively. Runoff and soil loss were measured from six furrows. At Denaro's farm, soil movement off the farm was measured at a taildrain outlet.

Sediment concentration from both rainfall and irrigation declined when cultivation had ceased, soil in the furrows had consolidated and when the cotton canopy provided surface cover. Total soil loss from rainfall and irrigation was approximately 4–5 t ha^{-1}. Rainstorms caused most of the seasonal soil loss, typically 3–4 t ha^{-1}. The critical soil erosion period was between pre-plant irrigation and canopy closure. Soil surface cover, peak runoff rate and furrow length explained 97% of variance in soil loss caused by rainfall. Furrow length was not significant in the soil loss model for irrigation (r^2 0·59).

Keywords: erosion, runoff, furrow length, cotton, tillage.

Introduction

The Emerald Irrigation Area (EIA) is predominantly summer cropping (12 000 ha) with cotton (*Gossypium hirsutum L.*) the main crop (10 000 ha). Other crops grown are soybean (*Glycine max L.*) and sunflowers (*Helianthus annuus L.*) Summer and its associated cultivation practices (fallowing, sowing, incrop cultivation and irrigation) coincide with the high intensity storm season when there is a high risk of field erosion.

Furrow irrigation in the EIA, because of the nature of the topography, is conducted on steeper gradients (up to 2%) to that normally irrigated in Australia (<0·2%). Soil erosion rates are likely to be higher from the EIA than from the gentler gradients typical of irrigation areas in Australia. Meyer *et al.* (1983) found that sediment transport capacity, and not sediment detachment, is usually the factor limiting soil loss from furrows with low slopes. The authors found sediment transport was 10–100 times greater on a 1·0% furrow gradient compared with a 0·2% furrow gradient.

Soil erosion in the EIA from rainfall and irrigation has caused siltation of culverts, main drains and roads. The impact of this erosion is a major concern.

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Farmers in the EIA have modified slope lengths by removing head ditches to increase furrow length. They believe longer furrows improve irrigation efficiency, reduce labour costs and reduce wastage of water. It is also believed that soil erosion is not affected by furrow length. However, Mech (1949) found soil erosion associated with irrigation occurred along the entire furrow, was greatest at the supply end, and that longer furrow lengths did not reduce erosion within furrows.

Fitzsimmons *et al.* (1978) showed that most soil erosion in irrigated fields is caused during pre-plant irrigation and that cultivation between irrigations may double soil loss. Dickey *et al.* (1984*a*), and Evans *et al.* (1982) also found that, when cultivation ceased, soil loss associated with irrigation events declined.

Soil cover can further reduce erosion. Stein *et al.* (1986) showed that the amount of crop residue in a furrow determined the rate of soil erosion. Dickey *et al.* (1984*b*) found that 20% soil cover reduced erosion by 50%. Their study was conducted on a steeper gradient (8%) than that commonly found in the EIA. Soil erosion from furrow layouts caused by irrigation or rainfall and the interaction between the two has not been studied extensively, and not at all in the EIA.

The main aims of this study are to determine via statistical description, rather than process modelling,

(i) the observed effect of furrow length on soil erosion,
(ii) the relative importance in an experimental study of rainfall and irrigation on soil erosion,
(iii) the measured interaction between irrigation and rainfall on erosion and runoff, and
(iv) the observed effect of taildrains on sediment transport.

Materials and Methods

Climate and Soils

The EIA is centred around Emerald, Queensland (148° 10′ E., 23° 32′ S.). The region has a semi-arid tropical environment. Rainfall is summer-dominant; long-term rainfall figures show that 66% of the rainfall occurs between November and March. Most erosive rainfall occurs in January as characterized by an Erosive Index (EI), described by Wischmeier and Smith (1978) (Table 1). During the study, September, October and January had greater than the corresponding long-term monthly averages.

However, December, February and March had an 80% (4 in 5 years) probability of receiving higher rainfall than occurred during the trial. The two experimental sites were located in the EIA on the farms of Mr S. Denaro (portion 143) and Mr. G. Roberts (portion 137). The project monitored runoff and soil loss over the 1986–87 cotton growing season (September–March).

The soil type at both sites was a black cracking clay (Vertisol, Mollic Torrert, fine montmorillonitic hyperthermic, 58% clay and pH 7·8). The Australian soil classification is Ug5·12 (Northcote 1971).

Site Layout

At both sites a short furrow length (SFL) and a long furrow length (LFL) were compared. Furrow lengths at Denaro's farm were 241 m (SFL) and 482 m (LFL), with a 1% slope gradient (Fig. 1). At Roberts' farm, furrows were 151 m (SFL) and 298 m (LFL) with a 1·3% slope (Fig. 2).

Furrows were formed 1 m apart. Six furrows were monitored and represented the machinery width used by the farmers. After the runoff water was discharged from the SFL, it was redirected into the furrows below the treatment. This allowed cotton to be grown below the SFL treatment and minimized any lateral water movement from the adjacent LFL treatment. Runoff from the furrows was then discharged into a taildrain.

Table 1. Long-term (1881–1985) monthly rainfall for Emerald and corresponding monthly rainfall for trial period (September 1986–March 1987)

Description	Month											
	S	O	N	D	J	F	M	A	M	J	J	A
Rainfall (1881–1985) (mm)	24	37	58	89	108	101	71	35	33	34	27	21
Denaro's farm (mm)	60	104	62	19	123	32	6					
Roberts' farm (mm)	63	116	77	14	114	27	10					
Rainfall probabilities (mm)												
20% of years rainfall exceeds	43	70	99	132	177	158	101	63	54	60	48	41
50% of years rainfall exceeds	11	30	49	79	93	75	55	19	23	21	15	11
80% of years rainfall exceeds	0	6	18	31	37	31	16	2	1	1	1	1
Average monthly EI as percentage of annual EI	1·0	1·8	11·4	21·6	33·5	12·3	10·8	4·2	0·6	0·3	1·1	1·4

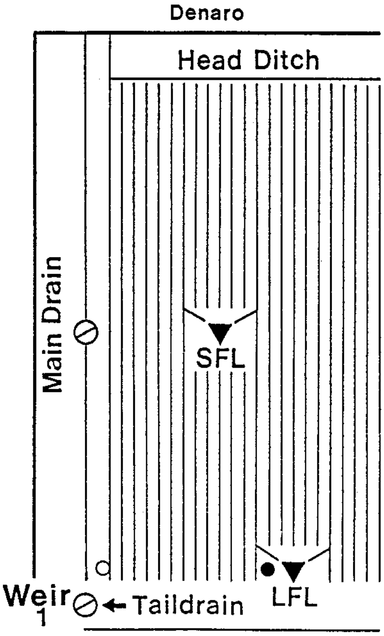

Fig. 1. The experimental layout at Denaro's farm. Short furrow length (SFL) 241 m, long furrow length (LFL) 482 m. Slope gradient 1%. At Weir 1, soil loss and runoff were measured from 100 m taildrain.

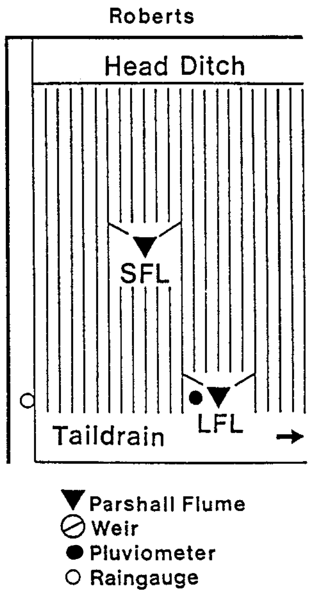

Fig. 2. The experiment layout at Roberts' farm. Short furrow length (SFL) 151 m, long furrow length (LFL) 298 m. Slope gradient 1·3%.

At Denaro's farm, runoff and soil loss were also measured at the outlet of a 100 m long taildrain (Weir 1). This enabled a comparison of soil loss between the LFL and taildrain outlet, and helped determine the efficiency of the taildrain to trap sediment. The taildrain had a 0·1% gradient (Fig. 1).

Data Collection

A pluviometer and a rain gauge were placed near the LFL flume at both sites to measure rainfall intensity and total rainfall, respectively.

A 150 mm Parshall flume and associated water-level sensor were used to calculate runoff from both treatments. A rectangular concrete weir (Weir 1) and water level sensor measured runoff from the taildrain at Denaro's farm.

Rainfall and flow height were recorded at 6 min time intervals on a data logger. Any errors in baseline values (due to electronic drift) were corrected by matching logged heights to manually recorded water-levels.

Water samples (1 L) were taken by hand every 6 min at the outlet of the flume, during all rainfall and irrigation runoff events. When irrigation flow rates were constant, or during the recession of a storm runoff, the interval between sampling was extended. Sediment concentration was determined by oven-drying.

Data Processing

A standard discharge rating curve was used to convert the height of flow in the flume to a runoff discharge rate q ($m^3\ s^{-1}$). Since the runoff discharge rate is dependent on catchment area A (m^2), the furrow length responses were compared on a unit area basis by using runoff rate ($m\ s^{-1}$), total depth of runoff (m) and total soil loss ($kg\ m^{-2}$).

Total depth of runoff was calculated from the equation

$$\text{Total depth of runoff} = \int_0^t \frac{q}{A}\, dt\,, \tag{1}$$

and total soil loss was found by integrating the product of runoff discharge rate and sediment concentration c ($kg\ m^{-3}$):

$$\text{Total soil loss} = \int_0^t \frac{(qc)}{A}\, dt \tag{2}$$

In this paper, the units for runoff discharge rate, runoff rate, total runoff and total soil loss have been converted to $L\ s^{-1}$, $mm\ hr^{-1}$, mm and $t\ ha^{-1}$.

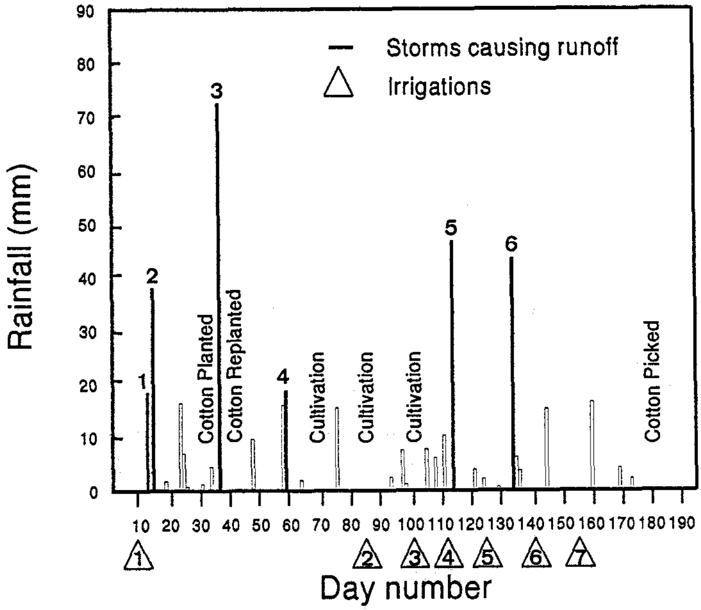

Fig. 3. Daily rainfall, irrigation and farm management practices undertaken during the trial period at Denaro's farm. Rainstorms that produced runoff have solid lines and are numbered 1–6. Irrigations are numbered and shown as triangles.

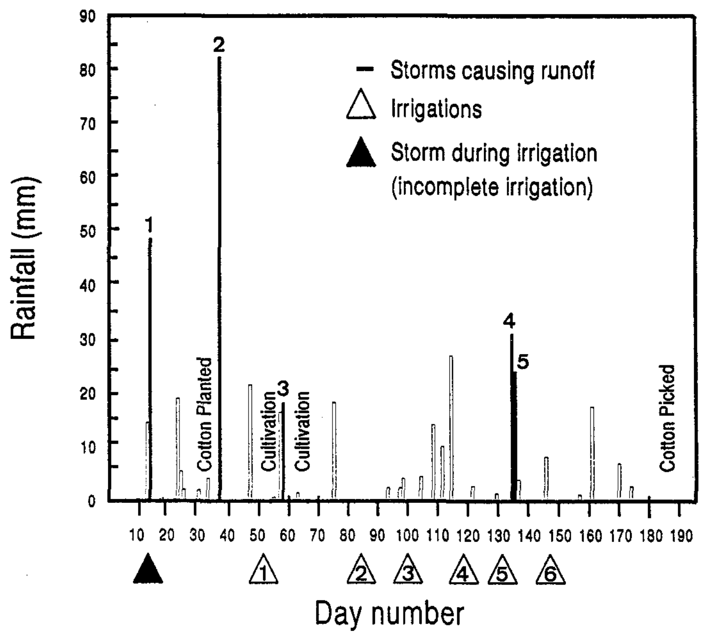

Fig. 4. Daily rainfall, irrigation and farm management practices undertaken during the trial period at Roberts' farm. Rainstorms that produced runoff have solid lines and are numbered 1–5. Irrigations are numbered and shown as triangles.

Rainfall and Irrigation

Six storms and seven irrigations contributed significant runoff and sediment at the Denaro farm (Fig. 3). At Roberts' farm, runoff occurred from five storms and six irrigations (Fig. 4). A storm and irrigation number is used to identify the individual events.

The study monitored soil erosion rates from the farmer's irrigation management. Furrows were flood irrigated using siphons placed in alternate furrows. Application rates of irrigation water were not measured. At Denaro's farm, the first and last two irrigations used 37·5 mm siphons, the other four irrigations used 31·2 mm siphons. Roberts used 31·2 mm siphons for all irrigations, except Irrigation 1 when 25 mm siphons were used in every row.

The first irrigation at both farms watered cotton beds before sowing. A 10 day irrigation cycle was used during the major cotton crop growth stage. The exception was Irrigation 6 at Denaro's farm and Irrigation 4 at Roberts' farm when rainfall increased the interval between irrigation cycles.

Irrigations were run until the full length of the field had been watered. The runoff duration from the SFL was longer because water discharged from the flume was used to irrigate the area below the SFL treatment (see Fig. 1).

Consequently, a common runoff duration of 3 h is used conveniently to compare runoff and soil loss from irrigations for the two furrow length treatments. All the irrigation data from both farms are used to produce a statistical description of soil loss from irrigation.

Tillage Management

At Denaro's farm, cotton was sown in 1 m rows and rolled on 21 October (35 days after the establishment of the experimental site). Rain on the following day caused a crust to form and seedling emergence was impaired. The crop was resown on 31 October. Three cultivations were carried out during the crop to control weeds and to reshape the cotton beds. The crop was picked on 28 March 1987. At Roberts' farm, cotton was sown on 18 October. There were two cultivations during the crop and the crop was picked on 20 March 1987.

The change in the cross sections of the six furrows, caused by cultivation and irrigation and rainstorm erosion events, was monitored adjacent to permanent reference points, at two positions on the SFL and four positions on the LFL. A measuring staff was placed across the top of the cotton beds, and the furrow cross-sectional shape was determined by measuring the vertical distance to the soil at 5 cm intervals along the staff.

The percentage of soil surface protected by stubble or crop canopy cover was visually estimated in 1 m^2 areas along the furrow length. Soil covers were taken after each irrigation and storm event. Photographs taken after the events were used to supplement the field observations of soil cover.

Results and Discussion

Furrow Length Comparison

Rainfall-induced erosion generally had higher sediment concentration from the LFL treatments at both farms (Tables 2 and 3). This is often associated with higher runoff discharge rates from storm events, particularly early in the season, when soil cover was low and when cotton beds had been freshly formed. As furrow length increases, runoff discharge increases, and the flow widens and detaches soil from the sides of the cotton beds. Mech (1949) described the process as 'streambank erosion'. At the start of the study, the cotton beds had steep sides, with typically a 50% side gradient. Fig. 5 shows that, following storm 1 at Roberts' farm, concentrated flow in the furrows detached soil from the sides of the cotton beds and widened the furrows. This caused the furrow cross-section to change from an original V-shape to a more trapezoidal shape. Sowing and cultivation operations reformed the cotton beds, which in turn were eroded by a sequence of irrigation and rainstorm events. By the end of the cotton growing season, the cotton beds had slumped and consolidated at both farms, and soil erosion under rain declined for both furrow lengths.

Storm 5, at both farms, is a good example of the decline in soil erosion late in the season. Both sites had relatively high peak runoff rate and discharge rates, yet had low average sediment concentration. Storm 5 occurred at both farms when the cotton canopy provided soil protection from rainfall, and incrop cultivation had ceased.

Nearing *et al.* (1990) observed that soils exhibit a large variation in erodibility with time, because of climatic, cropping and management influences. Meyer and Harmon (1992) found that a growing cotton crop progressively protects the soil from direct rainfall impact, and found a 90% decline in interrill and rill erodibility between cotton emergence and harvest of the crop. Norton and Brown (1992) also found that interrill and rill erodibility were higher on freshly formed furrows compared with older more consolidated furrows.

In the EIA study, soil erodibility under irrigation also varied during the season, depending on soil surface management and the stage of crop growth. Tables 4 and 5 show a marked reduction in sediment concentration between the first and final irrigation. The decline in sediment concentration occurred despite a higher peak runoff rate for the final irrigations at both farms. Dickey *et al.* (1984*a*) had a similar finding with 75% reduction in sediment between the first and fourth irrigation.

In the irrigations, infiltration along the LFL reduced both peak runoff rate and total runoff. Consequently, less runoff meant there was slightly less soil loss from the LFL. However, less soil loss does not mean there is less erosion on the

Table 2. Rainfall, runoff and soil loss from SFL and LFL treatments at Denaro's farm

Storm No.	Treat-ment	Cover (%)	Total rainfall (mm)	Max. I_6 (mm h^{-1})	Peak runoff rate (mm h^{-1})	Peak runoff discharge (L s^{-1})	Total runoff (mm)	Sediment concn (g L^{-1})	Soil loss (t ha^{-1})
1	SFL	10			8·3	3·0	14·7	1·9	0·28
	LFL	10	18·8	10	8·4	7·0	18·8	3·2	0·59
2	SFL	10			32·7	13·0	18·0	8·6	1·56
	LFL	10	36·6	84	22·8	18·0	22·0	7·7	1·7
3	SFL	5			4·5	2·0	16·2	2·0	0·33
	LFL	5	72·5	98	6·3	5·0	24·8	2·9	0·72
4	SFL	5			10·4	4·0	2·6	12·0	0·31
	LFL	5	19·8	86	6·9	5·0	2·0	14·4	0·29
5	SFL	90			25·9	10·0	23·9	1·5	0·36
	LFL	90	48·7	92	18·9	15·0	19·5	3·4	0·67
6	SFL	90			2·6	1·0	1·6	1·8	0·03
	LFL	90	45·9	81	0·5	4·0	0·5	2·1	0·01

Table 3. Rainfall, runoff and soil loss from SFL and LFL treatments at Roberts' farm

Storm No.	Treat-ment	Cover (%)	Total rainfall (mm)	Max. I_6 (mm h^{-1})	Peak runoff rate (mm h^{-1})	Peak runoff discharge (L s^{-1})	Total runoff (mm)	Sediment concn (g L^{-1})	Soil loss (t ha^{-1})
1	SFL	10			65·2	16·0	57·0	6·33	3·61[A]
	LFL	10	56·8	160	46·8	23·0	35·2	8·16	2·87
2	SFL	5			12·9	3·0	25·0	2·34	0·59
	LFL	5	82·4	110	10·1	5·0	28·6	2·41	0·70
3	SFL	5			4·1	1·0	0·7	—	—
	LFL	5	17·6	54	4·3	2·0	1·8	4·7	0·05
4	SFL	90			5·2	1·3	2·4	0·95	0·02
	LFL	90	34·0	76	5·7	3·0	6·8	0·49	0·03
5	SFL	90			49·5	12·0	14·2	1·12	0·16
	LFL	90	24·4	124	30·5	15·0	17·0	1·11	0·19

[A] Storm occurred during an irrigation when flow had only reached SFL.

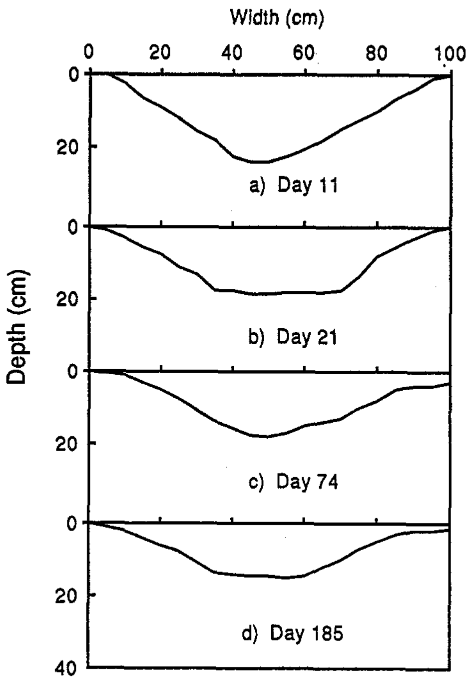

Fig. 5. Change in cross section of a typical furrow *(a)* prior to first irrigation, *(b)* following irrigation 1 and storm 1, *(c)* following last cultivation, and *(d)* towards the end of the cotton season. (Roberts' site, furrow 3.)

Table 4. Irrigation runoff and soil loss from SFL and LFL treatments for 3 h runoff durations at Denaro's farm

Irrigation No.	Treatment	Cover (%)	Peak runoff rate (mm h^{-1})	Peak runoff discharge (L s^{-1})	Total run-off (mm)	Sediment concn (g L^{-1})	Soil loss (t ha^{-1})
1	SFL	10	2·44	1·0	4·1	1·7	0·1
	LFL	10	0·64	0·5	0·7	3·6	0·02
2	SFL	50	3·97	1·6	7·3	2·2	0·2
	LFL	50	1·83	1·5	4·2	4·2	0·2
3	SFL	75	3·97	1·6	4·8	5·0	0·15
	LFL	75	2·93	2·4	10·9	2·4	0·4
4	SFL	90	4·04	1·6	7·2	1·1	0·2
	LFL	90	2·63	2·1	5·3	0·9	0·1
5	SFL	90	4·73	1·9	10·6	0·6	0·1
	LFL	90	2·59	2·1	6·5	1·3	0·1
6	SFL	90	3·97	1·6	7·8	0·3	0·05
	LFL	90	3·74	3·0	5·5	0·4	0·04
7	SFL	90	4·11	1·7	10·3	0·2	0·06
	LFL	90	4·44	3·6	8·0	0·2	0·03

Table 5. Irrigation runoff and soil loss from SFL and LFL treatments, for 3 h runoff durations at Roberts' farm

Irrigation No.	Treatment	Cover (%)	Peak runoff rate (mm h^{-1})	Peak runoff discharge (L s^{-1})	Total runoff (mm)	Sediment concn (g L^{-1})	Soil loss (t ha^{-1})
1	SFL	10	6·31	1·6	9·80	8·81	0·58
	LFL	10	1·00	0·5	2·40	2·69	0·06
2	SFL	30	3·97	1·0	6·60	1·80	0·10
	LFL	30	0·94	0·5	1·50	2·63	0·03
3	SFL	50	2·95	0·7	5·50	0·47	0·03
	LFL	50	1·26	0·6	3·30	0·74	0·03
4	SFL	70	2·19	0·5	3·90	6·00	0·20
	LFL	70	1·08	0·5	2·20	1·90	0·05
5	SFL	80	5·70	1·4	9·40	1·04	0·12
	LFL	80	1·89	0·9	4·70	0·40	0·02
6	SFL	90	6·65	1·7	13·70	0·32	0·12
	LFL	90	2·02	1·0	3·80	0·10	0·01

longer furrows. The soil loss on the SFL shows there is erosion taking place on the upper end of the field and along the entire furrow length. Carter *et al.* (1985) found that irrigation-induced erosion and resulting soil loss is greatest on the upper portions of fields where furrow stream size is largest and the energy to erode is greatest.

Table 6. The r^2 values of statistical analysis describing soil loss

Functional relation	Soil loss (t ha^{-1}) Rainfall	Irrigation
f(cover)	0·173	0·134
f(runoff)	0·702	0·035
f(peak discharge)	0·538	0·179
f(peak runoff rate)	0·573	0·130
f(rain, soil water deficit, runoff)	0·798	n.a.[A]
f(peak runoff, peak runoff×cover)	0·931	0·59

[A] n.a., not applicable.

Comparison of Erosion Associated with Rainfall and Irrigation Events

The soil loss pattern from rainfall differed sharply from that of irrigation. Irrigations are characterized by low sediment concentrations and runoff rates when compared with those from natural rainfall events. For example, Fig. 6 shows that for Storm 2 at Denaro's farm, peak sediment concentration coincided with the peak runoff rate. Most of the soil loss occurred during this period, through higher runoff streampower, raindrop impact and a larger exposed area—both bed and furrows were exposed to rainfall.

However, under irrigation, sediment concentration is almost constant with time (Fig. 7), with runoff increasing at a linear rate with time. Total soil loss from an irrigation is a function of runoff rate, sediment concentration and runoff duration

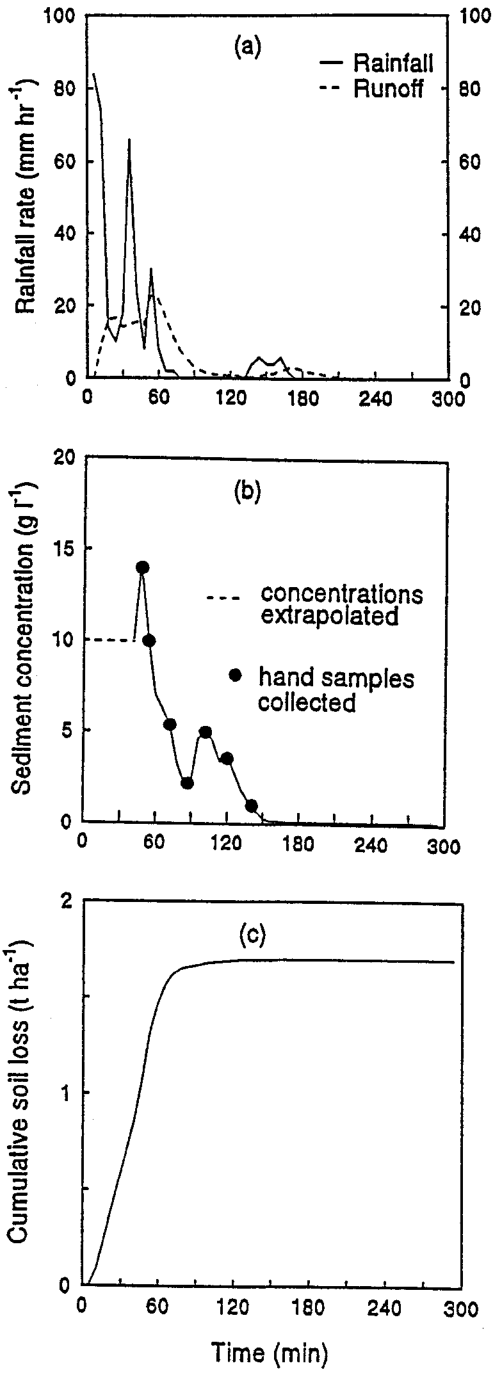

Fig. 6. Comparison of *(a)* runoff rate, *(b)* sediment concentration and *(c)* cumulative soil loss through time for a rainstorm (Storm 2, Denaro's farm).

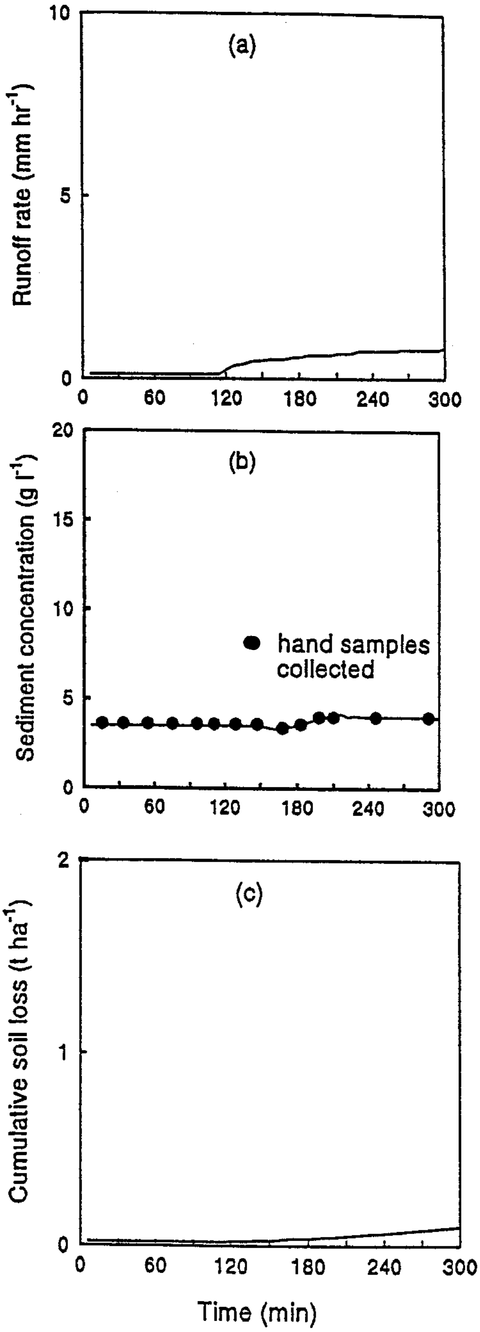

Fig. 7. Comparison of *(a)* runoff rate, *(b)* sediment concentration and *(c)* cumulative soil loss through time for an irrigation (Irrigation 1, Denaro's farm).

(equation 2). Consequently, irrigations should be managed to avoid unnecessary continuing flow and hence soil loss from furrows.

Rainfall caused most of the soil loss over the study period. For example, at Denaro's farm there was 4 t ha^{-1} total soil loss from the six storms and only 1 t ha^{-1} loss from seven irrigations at the LFL. The first four storms at Denaro's farm produced 2·8 and 3·3 t ha^{-1} soil loss before the cotton canopy closed on the SFL and LFL, respectively (Table 2). At Roberts' farm, storm 1 alone contributed up to 3·6 t ha^{-1} of the total soil loss associated with rainfall (Table 3). At the time of these storms, there was no crop sown, and the soil had low surface cover. Yoo and Touchton (1989) also found that the 'critical period' for erosion was between cotton sowing and the last cultivation. Protection of the soil surface by a summer growing crop, during the most erosive rainfall months of January and February, will reduce erosion, although the extent of erosion will still be strongly influenced by seasonal rainfall.

Interaction between Irrigation and Rainfall on Erosion

Storm 1 at Roberts' farm caused the highest soil erosion during the study. This storm occurred during an irrigation when only the SFL and the top half of the LFL had been watered. Consequently, the SFL had the largest peak runoff rate and total soil loss of all the storms, and the equivalent of all rainfall appeared as runoff (Table 3). On the LFL, storm runoff surged over the lower half of the field and caused rapid sediment detachment and furrow wall collapse. Hence, the LFL had a larger peak and average sediment concentration than the SFL. By the end of the storm, sediment concentrations were similar for the two furrow lengths. This is consistent with the observations of Govers (1991) and Poessen (1981), where high intensity rainfall on dry soil causes higher sediment concentration than from soil that is initially wet.

However, the soil water content at the time of a rainstorm can have a marked effect on runoff and hence soil loss. Both soil evaporation and particularly crop water use can result in low soil water contents that can substantially reduce storm runoff. For example, storm 6 at Denaro's farm had approximately 95% less runoff than storm 5. Yet, both storms had similar rainfall and intensity. Before storm 6 at Denaro's farm, the soil was quite dry compared with storm 5. There had been 9 days without an irrigation, and crop water use had caused cracks to form in the furrows. Consequently, most of the 46 mm rainfall infiltrated into the soil. In contrast, storm 5 occurred 2 days after an irrigation and caused 24 and 19 mm runoff from the respective furrow lengths. Thus, lower antecedent water contents reduce runoff and soil loss.

Soil Movement from the Farm

Not all sediment detached is transported from a farm property. Sediment can be deposited within furrows and taildrains. However, this sediment storage is often short-term, and can be readily re-entrained by a subsequent storm or irrigation event (Wallings 1983).

At Denaro's farm, sediment deposition was observed in the bottom of furrows following storm 1. Re-entrainment of this material is a possible explanation for the high sediment concentration from storm 2, two days later. Storm 4 at Denaro's farm and irrigations 1 and 4 at Roberts' farm are other events that have high sediment concentrations, and occurred soon after rainfall. Particularly, the SFL at Roberts' farm for irrigation 1 which had the highest concentration for all the irrigations.

Kinnell (1994) described the deposition that occurs within furrows as a 'dynamic depositional layer' (DDL), with soil erodibility also dynamic, and often varying between two extremes. The sediment in the DDL is a ready source of easily entrained material, and explains the high sediment concentrations following rainstorm events in the EIA study. In this study, the separation between the processes of interrill, rill erodibility and sediment re-entrainment was not measured. More research is required to determine the temporal changes to these parameters in the Emerald Irrigation Area.

The experimental layout at Denaro's farm enabled a comparison of soil erosion at gauging points at the end of the furrows and at the end of the taildrain. From the three storms where data were collected, sediment concentration was actually higher from the taildrain outlet than from the LFL. The average sediment concentrations from the taildrain at Denaro's farm for storms 3, 4 and 5 were 4·6, 13·7 and 4·9 g L^{-1}, respectively. In comparison, the LFL sediment concentrations were 2·9, 14·4 and 3·4 g L^{-1}. The magnitude of sediment re-entrainment from both furrows and taildrains would be related to annual and seasonal rainfall distribution, and would vary between storms.

Observations and measurements made at Robert's farm showed that uneven taildrain gradients caused ponding of water and sediment deposition at the end of furrows. While this may reduce soil movement from farmer's fields, it is not entirely beneficial, with potential severe soil erosion caused by overtopping of taildrains.

The soil erosion rate of 4–5 t ha^{-1} from the EIA is not large compared with upland situations. Freebairn and Wockner (1986) recorded soil erosion figures up to 100 t ha^{-1} from a single rainstorm event. However, a soil loss of 4 t ha^{-1} over 10 000 ha represents a total soil loss of 40 000 t. A total loss of this magnitude represents a major cost in desilting of culverts and main drains.

Statistical Description of Soil Loss for Rainfall and Irrigation

More process-based models such as WEPP (Laflen *et al.* 1991) were not used in the analysis of the data, since no detailed measurements were made to determine interill and rill erodibility parameters. Consequently, a statistical approach was used in the analysis of the data.

The combined data across rainstorms and irrigations from Roberts' and Denaro's farms were used to determine the main variables contributing to soil loss, using a multiple regression approach. The variables considered were peak runoff rate, peak discharge rate, total runoff, soil cover, total rainfall, maximum rainfall intensity for a 6 min period (I_6), erosion index (EI), days since tillage, soil water deficit and furrow length.

The regression of all the subsets of the above variables, their square terms and interactions were assessed on the basis of the amount of variance that could be accounted for (r^2), taking into consideration the number of variables in each regression.

The variables that best explained soil loss from runoff events were peak runoff rate, the product of peak runoff rate and cover, and furrow length (r^2 0·64,

$n = 47$). After these regression variables were fitted, it was found that there was no difference in response at the two sites, but a difference did exist between rainstorm and irrigation events.

Since, there was a significant difference between rainstorm and irrigation responses, the data were split and analysed separately. It was then found that furrow length was not significant for irrigation ($P > 0{\cdot}05$), and had a less defined/predictable response (r^2 $0{\cdot}59$).

The most suitable equations that accounted for soil loss (S) caused by rainfall and irrigation were

$$S_{\mathrm{r}} = -0{\cdot}4173 + 0{\cdot}0649\,\mathrm{PR} - 5{\cdot}903 \times 10^{-4}(\mathrm{PR} \times C) + 0{\cdot}0012\,\mathrm{FL} \qquad (3)$$

$$(n = 21; \quad r^2 = 0{\cdot}97);$$

$$S_{\mathrm{i}} = -0{\cdot}1382 + 0{\cdot}3356\,\mathrm{PR} - 0{\cdot}0027(\mathrm{PR} \times C) \qquad (4)$$

$$(n = 26; \quad r^2 = 0{\cdot}59),$$

where S_{r} is soil loss from rainfall (t ha^{-1}), S_{i} is soil loss from irrigation (t ha^{-1}), PR is peak runoff rate (mm h^{-1}), C is soil cover (%) and FL is furrow length (m).

The statistical analysis suggests that peak runoff rate and soil cover are the major factors that describe soil loss from both rainfall and irrigation. Process studies might in future determine this. The relationship is similar to the approach of Freebairn and Wockner (1986), except for the inclusion of furrow length for rainfall-induced erosion. In the description for soil loss from irrigation, soil cover explained 30% of the variation in the data, and peak runoff rate 13%. Bagnold (1977) has shown that peak runoff rate is an index of the peak runoff velocity or peak available streampower. Figs 6*a* and 6*c* showed that most soil loss was associated with the peak runoff rate, particularly early in the season when the furrows and beds had low soil cover and were most susceptible to erosion.

Unlike rainfall, runoff rates and soil erosion from irrigations can be controlled by management of irrigation flow rates in the furrows. Irrigation runoff rates can be reduced by the use of smaller siphon sizes, particularly early in the cotton season when soil cover is low and the soil is freshly cultivated and prone to erosion.

Equation (4) shows irrigation runoff rates (and hence irrigation water application rates) are less critical when there is high soil cover later in the crop. This was also shown at Denaro's farm when sediment concentration was reduced between the first and final irrigation, despite a higher peak runoff rate from the final irrigation. Sediment concentration was reduced on the SFL and LFL from $1{\cdot}7$ and $3{\cdot}6$ g L^{-1} to $0{\cdot}2$ g L^{-1} which is 88% and 94% reduction in concentration between the two irrigations, for the respective furrow lengths.

The retention of crop residue and protection of the soil surface by a cotton crop canopy are the main management options to reduce soil loss from both rainfall and irrigation in the EIA, particularly where farmers have modified slope lengths by removing head ditches to increase furrow length. Another option is to reduce the gradient of the furrows in the EIA by constructing the furrows at an angle across the slope.

Conclusions

A trial for 1 year can only describe the soil erosion trends in the EIA. Nevertheless, the study showed that rainfall can cause a major proportion of soil erosion and the critical erosion period is between pre-plant irrigation (September) and when the cotton canopy closed (December). Once cultivation stopped and the canopy closed, sediment concentration in runoff declined from both rainfall and irrigation runoff.

Statistical analysis indicated that peak runoff rate, surface cover and furrow length are the main factors describing rainfall induced soil loss in the EIA. The effect of furrow length on soil loss is reduced by the retention of soil surface cover. Furrow length did not have a significant effect on soil loss from irrigation ($P < 0 \cdot 05$). Further research is required on the temporal variation in interrill and rill erodibility and would help develop a more process-based erosion model.

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References

Bagnold, R. A. (1977). Bedload transport in natural rivers. *Water Resources Research* **13**, 303–12.

Carter, D. L., Berg, R. D., and Sanders, B. J. (1985). The effect of furrow irrigation erosion on crop productivity. *Soil Science Society of America Journal* **49**, 207–11.

Dickey, E. C., Eisenhauer, D. E., and Jasa, P. J. (1984*a*). Tillage influences on erosion during furrow irrigation. *Transactions, American Society of Agricultural Engineers* **24**, 1468–747.

Dickey, E. C., Shelton, D. P., Jasa, P. J., and Peterson, T. R. (1984*b*). Tillage, residue and erosion on moderately sloping soils. *Transactions, American Society of Agricultural Engineers* **27**, 1093–99.

Evans, R. G., Aarstad, J. S., and Miller, D. E. (1982). Integrating furrow irrigation with trash tillage techniques. American Society of Agricultural Engineers Paper 82–2578. St Josephs MI 49085.

Fitzsimmons, D. W., Busch, J. R., Lewis, G. W., and Berg, C. W. (1978). Controlling irrigation losses with proper management. American Society of Agricultural Engineers Paper 78–7090. St Josephs MI 49085.

Freebairn, D. M., and Wockner, G. H. (1986). 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. *Australian Journal of Soil Research* **24**, 135–58.

Govers, G. (1991). Time-dependency of runoff velocity and erosion: the effect of the initial soil moisture profile. *Earth Surface Processes and Landforms* **16**, 713–29.

Kinnell, P. I. A. (1994). The effect of pre-detached particles on soil erodibilities associated with erosion by rain-impacted flows. *Australian Journal of Soil Research* **32**, 127–42.

Laflen, J. M., Elliot, W. J., Simanton, J. R., Holzhey, C. S., and Kohl, K. D. (1991). WEPP soil erodibility experiments for rangeland and crop land soils. *Journal of Soil and Water Conservation* **46**, 39–44.

Mech, S. T. (1949). Effect of slope and length of run on erosion under irrigation. *Agricultural Engineering* **30**, 379–83, 389.

Meyer, L. D., and Harmon, W. C. (1992). Soil erosion varies during the crop year. *Transactions American Society of Agricultural Engineers* **35**, 459–64.

Meyer, L. D., Zuhdi, B. D., Coleman, N. L., and Prasad, S. N. (1983). Transport of sand-sized sediment along crop-row furrows. *Transactions American Society of Agricultural Engineers* **26**, 101–11.

Nearing, M. A., Lane, L. J., Alberts, E. E., and Laflen, J. M. (1990). Prediction technology for soil erosion by water: status and research needs. *Soil Science Society of America Journal* **54**, 1702–11.

Northcote, K. H. (1971). 'A Factual Key for the Recognition of Australian Soils.' (Rellim: Adelaide.)

Norton, L. D., and Brown, L. C. (1992). Time effect on water erosion for ridge tillage. *Transactions American Society of Agricultural Engineers* **35**, 473–8.

Poessen, J. (1981). Rainwash experiments on the erodibility of loose sediments. *Earth Surface Processes and Landforms* **6**, 285–307.

Stein, O. R., Neibling, W. H., Logan, T. J., and Moldenhauer, W. D. (1986). Runoff and soil loss as influenced by tillage and residue cover. *Soil Science Society of America Journal* **50**, 1527–31.

Wallings, D. E. (1983). The sediment delivery problem. *Journal of Hydrology* **65**, 209–37.

Wischmeier, W. H., and Smith, D. D. (1978). 'Predicting Rainfall-erosion Losses—A Guide to Conservation Planning.' U.S. Department of Agriculture Handbook No. 537.

Yoo, K. H., and Touchton, J. T. (1989). Runoff and soil loss by crop growth stage under three cotton tillage systems. *Journal of Soil and Water Conservation.* **44** (3), 225–8.

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