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Role of Plant Cover and Stock Trampling on Runoff and Soil Erosion from Semi-arid Wooded Rangelands

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Abstract

Relationships between plant cover, runoff and erosion of a massive red earth were investigated for a runoff zone of an intergrove area in a semi-arid wooded rangeland in eastern Australia. The measurements were carried out in small experimental paddocks with different stocking rates of sheep and kangaroos. A trailer-mounted rainfall simulator was used to apply rainfall at a time averaged rate of 30 mm h^{-1} to obtain runoff rates and sediment concentrations.

There was a significant negative relationship ($r^2 = 0 \cdot 58$; $P < 0 \cdot 01$) between final runoff rate and plant cover. It is probable that the plants increase infiltration and decrease runoff by (i) funnelling water down their stems and (ii) providing macropores at the base of the plant through which water can rapidly enter the soil.

However, there was no significant effect of plant cover on sediment concentration. Probable reasons for this are: (i) even though plant cover will absorb raindrop energy and decrease the erosive stress on the soil, the nature of the plants investigated is such that they may not be 100% effective in protecting the soil beneath them, and (ii) the distribution of contact cover provided by the base of the plants is highly patchy and thus relatively inefficient at reducing sediment concentration.

At zero cover final runoff rates from paddocks with a high and low stocking rate were similar, i.e. $23 \cdot 4$ and $22 \cdot 3$ mm h^{-1} respectively. However, at zero cover, the sediment concentration from the high stocking rate paddock was significantly ($P < 0 \cdot 01$) greater than that from the low stocking rate paddock. Greater hoof activity and lower organic matter (and hence lower structural stability) of the 0–20 mm layer in the high stocking rate paddock caused the soil surface to be more susceptible to erosion.

These results show that grazing by removing perennial grasses and pulverizing the surface soil can have a major impact on local water balances and erosion rates respectively within the intergrove areas. The implications of these results for the long-term stability of semi-arid mulga woodlands is briefly discussed.

Introduction

The semi-arid woodlands of eastern Australia are one of the most important types of rangelands in Australia and occupy an area of approximately 500 000 km^2. Although some cropping occurs along the eastern edge, these open savanna-like woodlands are used predominantly for extensive wool production. A highly variable climate means that it is very difficult to manage these woodlands, and severe shrub encroachment, pasture deterioration and soil erosion are common problems for pastoralists. These forms of land degradation have caused a major decline in production in many areas (Mills 1981).

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Rainfall is generally low in the semi-arid woodlands of eastern Australia and one of the major concerns is that many management practices have an adverse effect on the infiltration of rainfall and redistribution of runoff. The infiltration of rainfall and redistribution of runoff affect subsequent spatial variation in available soil-water and hence have significant effects on diversity and production in the rangelands (Noy-Meir 1973; Montaña 1992). Excessive runoff can also result in soil erosion. Soil surface conditions, especially plant cover, are critical parameters affecting infiltration of rainfall and redistribution of runoff. Therefore, a major objective in managing semi-arid woodlands is to control soil surface conditions to increase the infiltration of rainfall into the profile and minimize runoff and erosion.

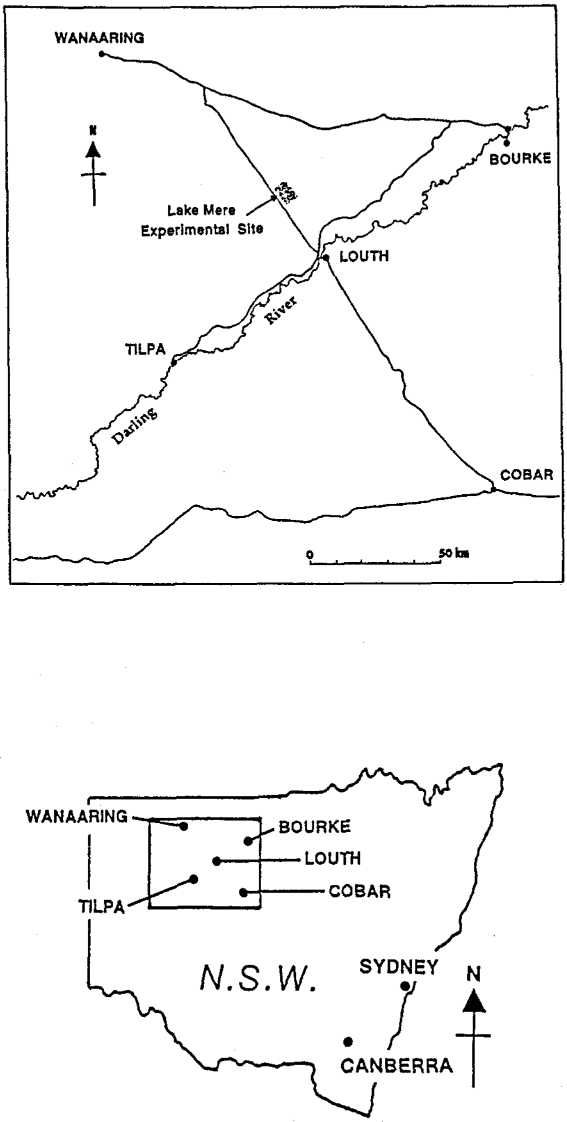

Fig. 1. Location of the 'Lake Mere' study site in the semi-arid rangelands of eastern Australia.

Grazing is the major disturbing force on soil surface conditions. This is due not only to the direct effects on soil physical properties, such as compacting the soil (Lull 1959), mechanically disrupting soil aggregates (Beckmann and Smith 1974), reducing soil aggregate stability (Knoll and Hopkins 1959) and destroying cryptogamic crusts (Mücher *et al.* 1988), but also to the indirect effects of defoliation (Hodgkinson 1993). Modification of soil physical properties together with reduction in the vegetative cover can result in decreased infiltration and excessive runoff and erosion, especially at high stocking rates (Blackburn 1984).

Therefore, to enable development of sustainable grazing management practices that do not adversely affect soil surface conditions, relationships between grazing, soil surface conditions and runoff and erosion need to be established. These relationships are particularly required on massive red earth soils, which are the most common and widely distributed soil type in the semi-arid woodlands of N.S.W. (Walker 1991).

The work described in this paper investigates relationships between soil surface conditions, particularly perennial grass cover, and runoff and erosion on a runoff zone of an intergrove area in a semi-arid wooded rangeland in eastern Australia. A mobile rainfall simulator (Grierson and Oades 1977) was used to develop relationships between runoff and erosion and soil surface conditions. Soil hydraulic properties (under ponded conditions) were also determined using a disc permeameter on bare, undisturbed surfaces, 2–3 m away from grass tussocks.

We concentrated our measurements on the runoff zone of the geomorphic sequence: (i) runoff zone, (ii) interception zone, and (iii) mulga grove, described by Greene (1992), because this is the zone that has the greatest slope and least cover and therefore is the zone most susceptible to runoff and erosion (Tongway and Ludwig 1990). Investigations of the runoff and erosion properties of the other two zones are to be described in subsequent papers.

Methods

The Study Site

The site was on 'Lake Mere' station, 35 km north of Louth, N.S.W. (30° 16′ S., 144° 54′ E.) (Fig. 1). It consisted of an area 1250 m by 1600 m of semi-arid mulga woodlands on which a sheep and kangaroo grazing study had been established in 1986 (Wilson 1991). Because the site was in near pristine conditions, it enabled the effects of the grazing treatments to be studied without major influence from prior management (Greene 1992). The area was subdivided into 12 paddocks, varying in size from 7·5 to 30 ha. Six of the paddocks contained six sheep at stocking rates of 0·3, 0·4, 0·5, 0·6, 0·7 and 0·8 sheep ha^{-1}. The other six paddocks contained six sheep and six kangaroos. The kangaroos were mainly western greys *(Macropus fuliginosus)*, but some paddocks contained a red kangaroo *(M. rufus)*. The latter paddocks were 50% larger, but were nominally of the same grazing intensity, on the basis that 1 kangaroo = 0·5 sheep in forage intake. The nominal stocking rates in the paddocks containing sheep and kangaroos were 0·2, 0·27, 0·33, 0·40, 0·47 and 0·53 sheep ha^{-1}.

The site was in an area of semi-arid mulga woodland that was comprised of a patterned sequence of groves and intergroves (Tongway and Ludwig 1990). The vegetation on the study site is dominated by mulga *(Acacia anaeura)* in the groves and contains a wide variety of perennial grasses, but predominantly woollybutt *(Eragrostis eriopoda)* and mulga grass *(Thyridolepis mitchelliana)*. The perennial grasses are scattered throughout the landscape, but mainly occur immediately upslope of the groves in the interception zone. Further upslope in the runoff zone of the intergrove areas their populations are sparse (Fig. 2). The median rainfall at the site is 275 mm, which is evenly distributed throughout the year. However, high intensity, short duration storms commonly occur each year, causing major redistributions of water from the runoff zones into the interception zones and mulga groves (Greene 1992).

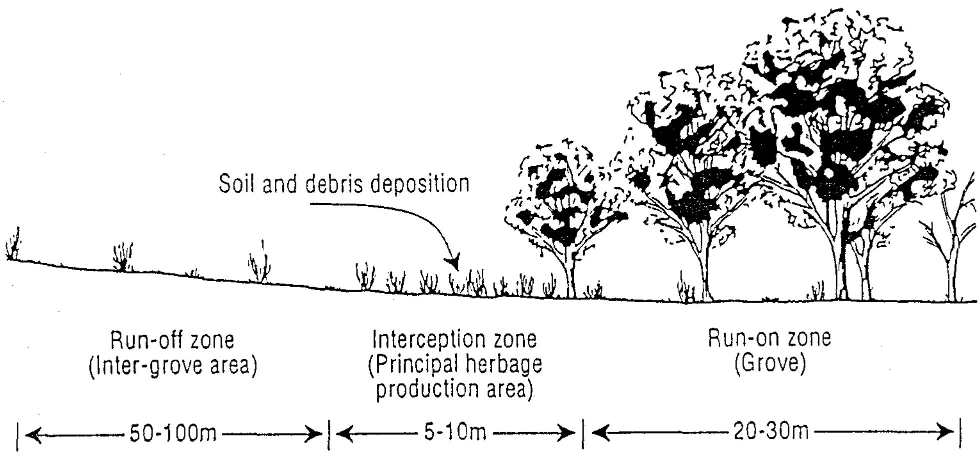

Fig. 2. Diagrammatic representation of an intergrove/grove in a semi-arid mulga woodland.(After Tongway 1991.)

The study site was situated on the Landsdowne land system (Walker 1991), which is comprised of undulating stony ridges of Cretaceous sandstones and shales and low tablelands of Tertiary silcretes. In places, the surface is partly covered with siliceous gravel and boulders. Relief is to 20 m, with narrow to broad dendritic drainage lines; slopes are less than 0·5%.

All measurements described in this paper were carried out on the runoff zones in the intergrove areas during the period from March to July 1991. The soil on the runoff zones was classified as a massive red earth Gn 2·12 (Northcote 1979), and consisted of a red-brown clay loam surface soil over a massive red texture B horizon (Greene and Sawtell 1992). In the U.S. Soil Taxonomy, the soil would be classified as a Xerollic Haplargid (Soil Survey Staff 1975). Analysis of the total soil from the 0–20 mm layer indicated 54% of it consists of stones and gravel >2·0 mm. Surface seals and crusts are a common feature of this soil–climate regime, particularly on the runoff zones (Greene and Ringrose-Voase 1994).

Rainfall Simulator Experiments

To investigate relationships between cover levels and runoff and erosion, 24 rainfall simulations were carried out on cover levels ranging from bare ground to approximately 80% total projected cover of perennial grasses. To achieve this range in cover levels, the rainfall simulations were carried out in two of the paddocks containing both sheep and kangaroos, one with a high (0·53 sheep ha^{-1}), and the other with a low (0·2 sheep ha^{-1}) stocking rate. The measurements with the rainfall simulator were carried out in two runoff zones, one near the south end and one near the north end, in each paddock. The use of two paddocks with different stocking rates also allowed the direct effects of grazing on soil surface properties to be determined.

For each of the simulations, rain was applied at a time averaged intensity of approximately 30 mm h^{-1} above a 1 m^2 steel quadrat, carefully located into the soil (Greene and Sawtell 1992). This intensity is similar to that of storms which can occur at the site (Greene 1993). The 1 m^2 steel quadrat was always located with the collection flume on the downslope side. The rainfall was applied using a 'rotating disc' type of simulator, which usually has a uniformity coefficient of >80% over a 1 m^2 area (Grierson and Oades 1977). A complete description of the rainfall simulator and methods of collecting runoff and erosion are given by Greene and Sawtell (1992).

Samples of the runoff from the 1 m^2 plot were collected until there was a steady runoff rate. This usually occurred after about 30–60 min, depending on the amount of perennial grass cover. At this stage, the application of rainfall was ceased, and measurements of the runoff continued until all the excess water on the plot had either infiltrated or drained into the collection flume. For each rainfall simulation, the following measurements were taken:

Soil cover levels: Prior to rainfall, a slide photograph of the 1 m^2 quadrat was taken vertically using a camera mounted on a stand 1·5 m above the plot. The slide was then projected onto a 100 square grid overlay and the number of grid intercepts over various types of cover was recorded. Preliminary studies had indicated that runoff was mainly determined by the total projected cover, which included the total areal cover of living and dead plants, as well as litter. The plant cover mainly consisted of woollybutt, with minor amounts of mulga grass. Although some stones usually occurred at the surface, they were only a minor part of the cover, i.e. <5% and were not included.

Microtopography measurements: A soil profilemeter (Semple and Leys 1987) containing a row of 50 vertical steel rods spaced at 20 mm intervals was used to assess the surface microtopography prior to rainfall. Five rows, spaced 200 mm apart and parallel with the contours of the plot, were used, giving a total of 250 measurements per plot. The profilemeter measured the microtopography after the ends of the rods came into direct contact with the soil surface, stones, or a grass tussock.

Soil hydraulic properties: Time-to-ponding (t_p), time-to-runoff (t_r), and final steady state runoff rate (r_f) were determined for each simulation run. Time-to-ponding (t_p) is defined as the time taken from the start of rainfall to when about 70% of the soil surface appears saturated (I. White, pers. comm.). Time-to-runoff (t_r) is defined as the time taken from the start of rainfall to when runoff was first measured in the flume. During the application of rainfall, runoff samples were collected at 1 min intervals for determination of runoff rates. Five samples were bulked for determination of sediment concentration, which was measured by oven drying subsamples of the runoff at 105°C.

After the cessation of rainfall, the collection of runoff samples was continued at 0·5 min intervals until all the water inside the quadrat had disappeared. The volume of these final runoff samples and the final steady state infiltration rates were used to estimate the volume of water on the surface at the time rain ceased and hence the mean flow depth of water on the soil surface at steady state (J. Huang, pers. comm.). Stone *et al.* (1993) also used a similar approach in runoff modelling.

Soil physical properties: Following each simulation run, after the excess water on the plots had disappeared, a disturbed sample of moist soil (consisting of a composite of 20 subsamples) was taken from the 0–20 mm layer inside the quadrat and placed in a plastic bag for transportation back to Canberra. Upon arrival, the samples were air dried and measurements of aggregate stability, particle size analysis (Loveday 1974) and total carbon content were carried out. Particle size analysis of the <2·0 mm size fraction indicated that the 0–20 mm layer from the paddock containing a nominal stocking rate of 0·2 sheep ha^{-1} consisted of 25·5% clay, 7·8% silt, 54·3% fine sand and 9·5% coarse sand. The corresponding soil from the paddock containing a nominal stocking rate of 0·53 sheep ha^{-1} consisted of 29·1% clay, 8·5% silt, 50·8% fine sand and 9·7% coarse sand. Even though these differences in particle size analysis between paddocks were significant at 5% and 1% for the clay and fine sand fractions respectively, they were not considered to be of any practical significance.

The total carbon content was measured by heating a 1·0 g sample of soil to 1200°C in a Leco CR-12 furnace fitted with an infrared CO_2 detector (Merry and Spouncer 1988). Aggregate stability was measured using the wet-sieving method (Kemper and Rosenau 1986). This method involves rapidly immersing a 20 g sample of air-dried soil (<10 mm size fraction) into water, followed by wet-sieving for 5 min (150 oscillations). Four sieve sizes (2·0, 1·0, 0·5 and 0·25 mm) were used. The results are expressed as % <0·25 mm and a mean-weight-diameter (MWD) value. The MWD is the sum of the percentage of soil on each sieve multiplied by the mean diameter of adjacent sieves (in this case, 6·0, 3·0, 1·5, 0·75, 0·375 and 0·125 mm), i.e.

$$\text{MWD} = (\sum \text{per cent of sample on sieve} \times \text{mean intersieve size}).$$

Disc Permeameter Measurements

For each rainfall simulation run, measurements of soil hydraulic properties (sorptivity, steady state infiltration rate and saturated hydraulic conductivity) were also carried out within 3–5 m of the area of the simulation run. Infiltration measurements were made on bare, undisturbed surfaces, at least 2–3 m away from tussocks, using disc permeameters (200 mm diameter) that supplied water at a potential of +10 mm. Perroux and White (1988) have discussed how the disc permeameter can be used in the field to measure three-dimensional infiltration rates under ponded and non-ponded conditions. The water used for the measurements had an electrical conductivity of $0 \cdot 07$ dS m^{-1}. Initial and final water contents were also determined. Immediately adjacent to the area where the infiltration measurements were carried out, the bulk density of the soil was measured with undisturbed cores of 70 mm diam. and 20 mm depth. The saturated hydraulic conductivity was calculated according to the method of White (1988).

Statistical Methods

Results from the two grazing regimes were analysed using a one-way analysis of variance and regression analysis (Snedecor and Cochran 1980), and significant differences noted for $P < 0 \cdot 05$ and $<0 \cdot 01$.

Results

Rainfall Simulator Measurements

As most of the soil surface in the paddock with the high stocking rate ($0 \cdot 53$ sheep ha^{-1}) was completely devoid of plant cover (i.e. $C = 0\%$, where C is the amount of cover), only eight rainfall simulations were carried out in this paddock. To achieve a range of cover levels up to approx. 80%, the remaining 16 simulations were carried out in the paddock with the lower stocking rate, i.e. $0 \cdot 2$ sheep ha^{-1}.

When simulated rainfall was applied at 30 mm h^{-1}, there was initially no runoff. However, after approximately 3 min, some ponding occurred, followed by runoff after approximately 10–13 min. The runoff rate then increased rapidly, reaching a steady value after >20 min (Greene and Sawtell 1992). For all the simulation runs, there was a linear relationship ($r > 0 \cdot 99$) between cumulative sediment loss and time. The slope of this line yields the rate of sediment loss. Unfortunately, sediment concentration values were not measured for five of the simulations in the low stocking rate paddock.

Table 1 lists, for each of the cover levels on the high and low stocking rate paddocks, the corresponding values of time to ponding (t_p), time to runoff (t_r), sediment loss rate (g h^{-1}), final runoff rate (mm h^{-1}) and the final sediment concentration (g L^{-1}). The sediment loss rates listed in Table 1 were calculated over both (*a*) the entire time sediment was collected (average sediment loss rate) and (*b*) the final 5 min sediment was collected (final sediment loss rate). In the majority of simulation runs, there was very little difference in sediment loss rates calculated using either method. The fact that the sediment loss rate was generally unchanged even after 40 min suggests that the soil surface was already at equilibrium prior to the commencement of rainfall.

Effect of plant cover on final runoff rate and final sediment concentration

Effects of a range of plant cover levels (0–80%) on final runoff rate and final sediment concentration were investigated at a constant stocking rate using the data from the low ($0 \cdot 2$ sheep ha^{-1}) stocking rate paddock. The values for final sediment concentration were obtained by dividing the final sediment loss rate (calculated over the final 5 min) by the volumetric unit discharge of water. The volumetric unit discharge of water was obtained by multiplying the final runoff rate (calculated over the final 5 min) by the area of the plot.

Table 1. Plant cover, time to ponding, time to runoff, runoff and sediment values (*a*, calculated over the entire time sediment was collected; *b*, calculated over the final 5 min sediment was collected) for the rainfall simulations on the high (H) and low (L) stocking rate paddocks

Stocking rate	Plant cover (%)	Time to ponding (T_p) (min)	Time to runoff (T_r) (min)	Av. sediment loss rate (*a*) (gh^{-1})	Final sediment loss rate (*b*) (gh^{-1})	Final runoff rate (*b*) (mm h^{-1})	Final sediment concn. (*b*) (g L^{-1})
H	0·0	7·5	11·0	6·66	5·59	20·0	0·280
H	0·0	6·5	10·0	7·14	5·59	22·3	0·251
H	0·0	8·5	15·0	4·04	2·66	25·7	0·104
H	0·0	5·5	10·0	7·14	8·22	26·4	0·311
H	0·0	6·0	10·5	7·26	6·95	24·6	0·283
H	0·0	5·3	10·5	5·84	5·35	22·7	0·236
H	1·2	5·5	10·0	8·76	7·64	22·3	0·343
H	1·2	4·0	7·0	5·88	5·11	23·2	0·220
L	0·0	8·5	13·0	3·60	3·34	23·4	0·143
L	0·0	7·0	12·5	6·06	5·49	21·3	0·256
L	5·0	*	*	*	*	25·5	*
L	10·0	*	*	*	*	23·1	*
L	16·1	8·0	23·0	2·05	1·80	13·8	0·130
L	21·0	7·0	19·0	1·09	1·37	11·0	0·125
L	24·7	8·3	12·0	4·34	2·15	22·3	0·096
L	25·0	*	*	*	*	17·0	*
L	27·2	6·5	15·0	2·63	2·66	13·8	0·193
L	29·6	5·0	8·0	2·50	1·99	20·6	0·097
L	35·0	*	*	*	*	14·3	*
L	39·5	6·5	12·0	5·18	4·58	17·5	0·262
L	54·3	7·5	11·0	2·30	1·55	13·6	0·114
L	60·0	*	*	*	*	11·5	*
L	69·1	6·0	9·0	2·46	2·64	16·0	0·165
L	77·8	7·0	13·0	1·80	1·61	10·6	0·152

* Denotes missing data.

For the low stocking rate treatment, there was a highly significant relationship ($r^2 = 0 \cdot 45$; $P < 0 \cdot 01$) between the final runoff rate, in mm h^{-1}, and plant cover. However, one of the plots had much lower runoff, i.e. 11·0 mm h^{-1}, than would have been expected (18·6 mm h^{-1}) from the cover, which was 21%. Closer examination of this plot revealed that it was atypical compared with the other plots in that it had a high coverage of stones and the plant cover was made up of several small grass tussocks. Stones and rock fragments at the soil surface can increase infiltration (Poesen *et al.* 1990) and several small tussocks would probably be more efficient at conducting water into the soil than just one or two large tussocks as is the usual case. As both of these factors would contribute to a lower runoff than predicted, this point was omitted. As a result, the fit is improved considerably ($r^2 = 0 \cdot 58$; $P < 0 \cdot 01$). This relationship is shown in Fig. 3.

At 0% cover, the final runoff rate calculated from the regression equation is 22·3 mm h^{-1}. The eight final runoff rates from the high stocking rate paddock are also shown in Fig. 3. The average of these eight runoff values, i.e. $23 \cdot 4$ mm h^{-1}, is not significantly different from the average final runoff rate ($22 \cdot 3$ mm h^{-1}) at 0% cover for the low stocking rate paddock. Therefore, we conclude that the two stocking regimes do not have any major influence on runoff and infiltration other than through their effect on cover.

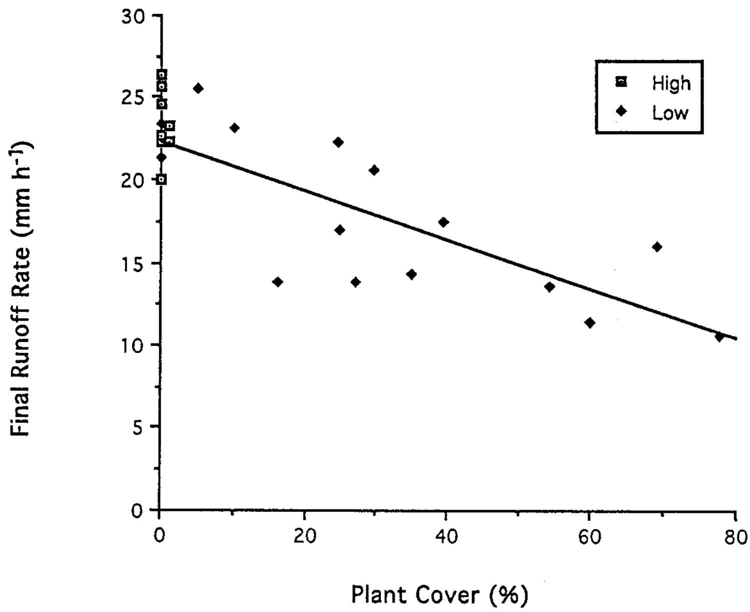

Fig. 3. Effect of plant cover on final runoff rate in high and low stocking rate paddocks. Note that the plot having 21% cover has been omitted from the graph. The regression line is for the low stocking rate only:

Regression equation: $y = 22 \cdot 3 – 0 \cdot 15x$ $(r^2 = 0 \cdot 58;\ n = 15;\ P < 0 \cdot 01)$.

To further investigate the effect of plant cover on infiltration, we fitted first-order autoregressive processes (Diggle 1990) to the sequences of heights measured by the profilemeter for each plot. There was a highly significant relationship between runoff and the logarithm of the estimated prediction variance which is a convenient measure of local variability ($r^2 = 0 \cdot 57$, $P < 0 \cdot 01$). However, this analysis was only of limited value because data are only available for 11 of the plots from the low stocking rate paddock. The correlation between cover and log prediction variance for these plots is $0 \cdot 60$.

Fig. 4 shows that, at a constant low stocking rate of $0 \cdot 2$ sheep ha^{-1}, there is a non-significant relationship between the final sediment concentration and cover ($r^2 = 0 \cdot 021$; $P = 0 \cdot 69$). Note that because the plot having 21% cover was atypical, it has also been omitted from this graph.

Effect of grazing rate on time to ponding (t_p), time to runoff (t_r) and sediment loss rate

The eight sediment concentration values from the high stocking rate paddock are also shown in Fig. 4. Their average value of $0 \cdot 253$ g L^{-1} is significantly

($P < 0{\cdot}01$) greater the value of $0{\cdot}161\ \mathrm{g\,L^{-1}}$ obtained for the low stocking rate paddock (Table 2). Table 2 also lists the means of the time to ponding and time to runoff for the high and low stocking rate paddocks. The average sediment loss rates for both the high and low stocking rate paddocks when there was zero or 1% cover are also given. Table 2 shows that there is no significant difference in both the time to ponding and time to runoff between the high and low stocking rate paddocks.

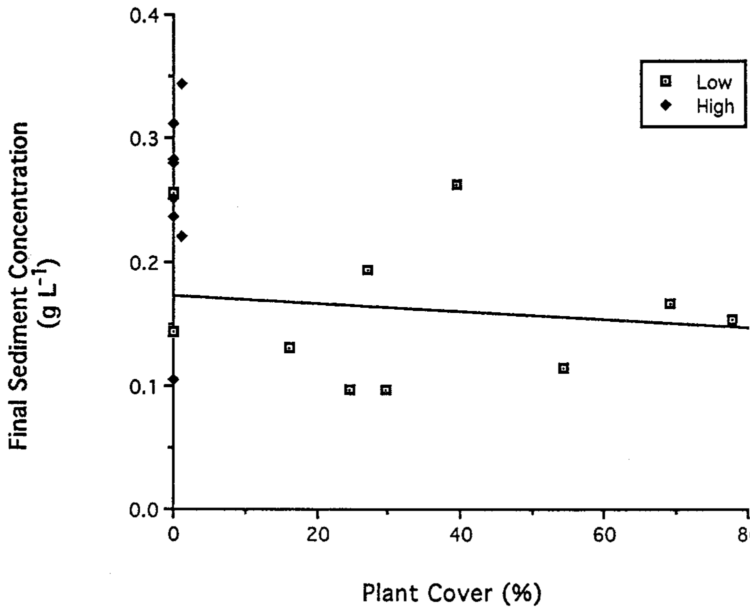

Fig. 4. Effect of plant cover on final sediment concentration in high and low stocking rate paddocks. Note that the plot having 21% cover has been omitted from the graph. The regression line is for the low stocking rate only:

Regression equation: $y = 0{\cdot}172\text{–}3{\cdot}2x$; $(r^2) = 0{\cdot}021$; n = 15 ($P = 0{\cdot}69$).

Table 2. Effects of stocking rate on soil hydraulic properties (measured with a rainfall simulator) of a massive red earth soil in the semi-arid wooded rangelands

Soil hydraulic Properties	Mean values[A] Stocking rate (sheep $\mathrm{ha^{-1}}$)[B] 0·2	0·53	Significance $P < 0{\cdot}01$
Sediment concn ($\mathrm{g\ L^{-1}}$)[C]	0·161 (±0·019)[A]	0·253 (±0·026)	
Time to ponding (min)[D]	7·0 (±0·3)	6·1 (±0·5)	n.s.[E]
Time to runoff (min)[D]	13·4 (±1·3)	10·5 (±0·8)	n.s.
Av. sed. loss rate ($\mathrm{g\ h^{-1}}$)[D]	4·83 (±1·23)	6·59 (±0·49)	n.s.

[A] Values in parentheses are ±standard errors of the mean.
[B] Both stocking rates consist of sheep and kangaroos.
[C] Note that the plot in the low grazing treatment having 21% cover has not been included in this analysis.
[D] Analysis only for plots having zero or 1% cover.
[E] n.s., not significant.

Fig. 5 shows regression lines (with standard errors) for cumulative sediment loss with time for the first 40 min after runoff commenced for both the low and high stocking rate paddocks when there was zero or 1% cover. For both stocking rates, there was a linear relationship ($r^2 > 0 \cdot 99$), with the higher stocking rate paddock having a greater rate of sediment loss ($6 \cdot 48$ g h^{-1}) than the lower stocking rate paddock ($4 \cdot 89$ g h^{-1}). These rates of sediment loss are very similar to the average sediment loss rates for the corresponding treatments in Table 2, i.e. $6 \cdot 59$ and $4 \cdot 83$ g h^{-1} respectively. However, our statistical analysis in Table 2 indicates that these two rates of sediment loss are not significantly different. This is a consequence of having only a small amount of data, i.e. two plots, with zero cover at the $0 \cdot 2$ sheep ha^{-1} grazing rate. These two plots yielded quite different sediment concentrations (Table 1), i.e. $0 \cdot 143$ and $0 \cdot 256$ g L^{-1}, while the corresponding runoff rates, i.e. $23 \cdot 4$ and $21 \cdot 3$ mm h^{-1} respectively, were not significantly different. This difference in sediment concentration was the major contributor to the high standard error of $1 \cdot 23$ g h^{-1} associated with the average sediment loss rate for the low ($0 \cdot 2$ sheep ha^{-1}) grazing rate treatment. It follows that because sediment concentration is not influenced by cover in our experiments, had we done a similar number of plots with no cover on the low grazing rate paddock as we did on the high grazing rate paddock, the average sediment loss rate for the low grazing rate treatment would not have been much different from the value of $4 \cdot 83$ g h^{-1} and would have been significantly different from the $6 \cdot 59$ g h^{-1} obtained for the high grazing rate treatment.

Soil Physical Properties

Table 3 compares the means of the various soil physical properties for the two stocking rates measured on soil samples taken from the 1 m^2 quadrat after the

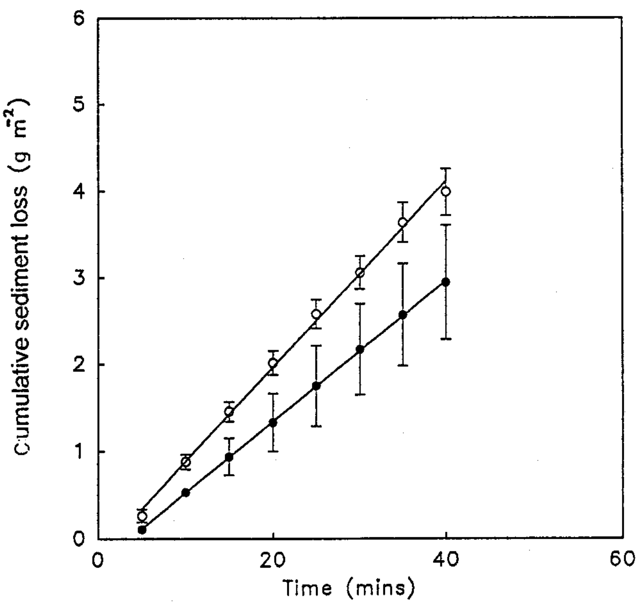

Fig. 5. Regressions of the mean cumulative sediment loss (with standard errors) against time for the first 40 min after runoff commenced for both the low (●) and high (○) stocking rate paddocks when cover is zero or 1%.

rainfall simulations. In general, the wet-sieving results show that the stability of the soil surface in the high stocking rate paddock is significantly ($P < 0 \cdot 05$) less than that in the low stocking rate paddock, i.e. after immersion wetting, the surface aggregates from the 0–20 mm depth in the high stocking rate paddock have a lower MWD (135·8) than those in the low stocking rate paddock (MWD 186·3).

Table 3. Soil physical properties measured on soil samples from the 0–20 mm layer inside the 1 m^2 quadrat after the rainfall simulations

Soil physical property	Mean values[A] Stocking rate (sheep ha^{-1})[B] 0·2	0·53	Significance
Aggregate Stability			
(MWD)[C]	186·3(±12·9)	135·8(±13·6)	$P < 0 \cdot 05$
% <0·25 mm	58·2(±2·2)	67·3(±2·8)	$P < 0 \cdot 05$
Total carbon content (%)	1·24(±0·08)	0·98(±0·06)	$P < 0 \cdot 05$
Bulk density (Mg m^{-3})	1·47(±0·02)	1·42(±0·01)	n.s.

[A] Means (with standard errors) from all rainfall simulations.
[B] Both stocking rates consist of sheep and kangaroos.
[C] The values given here are dimensionless according to the convention given by Kemper and Rosenau (1986). These values convert to 1·36 and 1·86 mm for the high and low stocking rates respectively.

However, there are possible limitations in the wet-sieving data presented in this paper. Firstly, MWD, as an index of stability, is strongly responsive to the coarser size fractions, and less sensitive to the proportions of fine particles. Infiltration in the field is largely determined by the proportion of fine particles, i.e. <0·1–0·5 mm (R. Loch, pers. comm.). Therefore, we have also compared the amount of <0·25 mm material formed after wet-sieving soil from the two stocking rates. Table 3 shows that the soil from the high stocking rate treatment has undergone significantly ($P < 0 \cdot 05$) more breakdown into <0·25 mm material (67·3%) than soil from the low stocking rate treatment (58·2%). Secondly, the procedure of taking a wet sample under the simulator, drying it and then re-wetting it, may increase the extent of breakdown. However, dry-sieving measurements showed that this effect is relatively small, the amount of material <2 mm increasing from 57% in the dried sample to 76% after wet-sieving.

The total carbon content in the high stocking rate paddock (0·98%) is also significantly ($P < 0 \cdot 05$) less than that in the low stocking rate paddock (1·24%). A linear regression analysis was carried out for all the samples from the 0–20 mm depth between their organic carbon content and their aggregate stability (MWD). The organic carbon content was shown to be highly correlated ($r^2 = 0 \cdot 53$, $P < 0 \cdot 001$) with the MWD. High correlations between organic carbon content and aggregate stability have also been demonstrated for a range of other soils (Tisdall and Oades 1980; Chaney and Swift 1984).

Table 3 shows that there was no significant difference in the bulk density of the 0–20 mm layer measured in 1991 between the high and low stocking rates, i.e. 1·42 and 1·47 Mg m^{-3} respectively. These values were also similar to the value of 1·48 Mg m^{-3} measured in 1986 (Greene 1992).

Disc Permeameter Measurements

Table 4 lists the values of steady state infiltration rate, sorptivity, and saturated hydraulic conductivity, measured in 1991, on areas of bare soil 2–3 m away from grass tussocks in the two paddocks with different stocking rates. It shows that there are no significant differences in these parameters (measured with the disc permeameter) between the low and high stocking rates. The baseline values of these parameters, which were measured in 1986 at the start of the experiment (Greene 1992), are also given to compare with the 1991 values. The 1986 values are also similar to those measured in 1991 for both stocking rates.

Table 4. Soil hydraulic properties measured in 1991 with the disc permeameter in both stocking rates on areas of bare soil away from grass tussocks (compared with 1986 values)

Soil hydraulic property	Mean values[A] Stocking rate (sheep ha^{-1})[B] 0·2	0·53	Significance	1986 values
Steady state infiltration rate (mm h^{-1})	23·0(±4·1)[B]	18·3(±2·9)	n.s.	25·0
Sorptivity (mm $s^{-1/2}$)	0·26(±0·04)	0·29(±0·04)	n.s.	0·22
Saturated hydraulic conductivity (mm h^{-1})	17·7(±3·3)	12·6(±2·1)	n.s.	20·0

[A] Values in parentheses are ±standard errors of the mean.
[B] Both stocking rates consist of sheep and kangaroos.

Discussion

In rangelands, the main management factor influencing surface soil conditions, and hence runoff and erosion, is grazing. Grazing can affect surface soil conditions by both (i) the indirect effect due to plant cover being defoliated and the concomitant effect this has on runoff and sediment concentration in the immediate vicinity of the grass tussock, and (ii) the direct effects of the grazing animal (such as compaction and pulverization) on the bare soil surface away from the tussocks. The other major factor influencing surface soil conditions, especially in the bare unprotected areas away from grass tussocks, will be (iii) rainfall. The following sections deal with each of these effects separately, and then finally their overall implications on the long-term stability of semi-arid mulga woodlands are discussed.

Indirect Effect of Grazing on Plant Cover and on Runoff and Sediment Concentration

Runoff

The present study highlights the importance of perennial grass cover in the partitioning of rainfall into infiltration and runoff in the intergrove areas in a semi-arid mulga woodland. In our experiments, plant cover significantly reduced runoff rate (Fig. 3) through its effect on infiltration. Eldridge and Rothon (1992) also showed that plant cover reduced the amount of runoff. Various mechanisms by which plant cover influences infiltration have been proposed. For example, De Ploey (1982) has shown that stemflow can concentrate an important amount

Fig. 6. Infiltration patterns observed on a massive red earth soil on the runoff zones after approximately 30 mm of simulated rainfall at 30 mm h^{-1}: (*a*) under perennial grasses and (*b*) bare surface.

of rainfall on the base of sods and tussocks. Dunne *et al.* (1991) also discussed how macropores at the base of the tussocks are generated by rootholes, burrows of microfauna, and interpedal spaces between large soil aggregates stabilized by organic matter. These macropores allow the rainwater to rapidly infiltrate into the soil (Lyford and Qashu 1969; Scholte 1989).

In the current study, it is likely that both the above mechanisms, i.e. stemflow and flow down macropores, are operating to decrease runoff and increase infiltration. Fig. 6*a* shows the effect of macropore flow on the infiltration pattern in a quadrat containing perennial grasses. In places, the wetting front has reached depths >15 cm. Similar effects of root and macrofaunal activity on macropore flow have been shown by Packer *et al.* (1992) in long-term tillage trials. The above examples are in marked contrast to that which occurs in a quadrat without perennial grasses, where there was considerable runoff and the depth of the wetting front is <5 cm (Fig. 6*b*). Similar measurements of infiltration using a disc permeameter have also been carried out over perennial grasses and bare areas (Rath 1993). These measurements also showed perennial grasses increased infiltration.

The results from the analysis of the profile meter data using autoregressive processes indicate that, in part, plant cover also increases infiltration and reduces runoff by increasing local variability in the soil microtopography. This increase in microtopography, or surface roughness, by grass butts would increase the detention of runoff and hence lead to greater infiltration.

The r^2 value obtained in the runoff/cover relationship in our experiments, i.e. 0·58, is as good as other values obtained for similar experiments. For example, McIvor *et al.* (1994) found, using large field plots, that for rainfall intensities in the range 25–45 mm h^{-1}, the r^2 value for the runoff/cover relationship was 0·53.

Sediment concentration

Other studies in the semi-arid rangelands (Elwell and Stocking 1974; Elwell 1980) have demonstrated the importance of cover in erosion control and shown a negative exponential relationship between soil loss and vegetative cover. The rate at which soil is lost from an eroding surface is given by the product of the volumetric discharge of water (q) and sediment concentration (n). Kinnell (1991) developed an empirical equation for non-vegetated areas for situations where drop impact has a dominant influence on particle detachment and the subsequent transport of detached particles by shallow flow,

$$n = k_1 \, R \, f(S) , \tag{1}$$

where k_1 is a soil-related factor, R is rainfall rate and $f(S)$ is a function related to slope gradient. When vegetative cover is involved, equation (1) becomes

$$n = k_1 \, R \, f(C) \, f(S) , \tag{2}$$

where $f(C)$ is a function that accounts for the ability of the cover to protect the soil from raindrop impact. Because, in our experiments, R and S are constant, the sediment concentration is directly related to the product of k_1, the soil erodibility factor, and $f(C)$. The factor k_1 also varies inversely with flow depth (Kinnell *et al.* 1990; Kinnell 1991).

Because cover protects the soil surface against raindrop impact (Dunne *et al.* 1991), the lack of a significant effect of plant cover on sediment concentration (Fig. 4) is contrary to the expectation that,

$$f(C) = 1 - C/100\,. \tag{3}$$

However, in the current experiments, there are a number of factors that may cause the plant cover to be ineffective at reducing sediment concentration. Firstly, even though plant cover will normally absorb some of the raindrop energy and decrease the erosive stress on the soil, the nature of the woollybutt and mulga grass plants is such that they may not be 100% effective in protecting the soil beneath them. The plant stems comprising the canopies of woollybutt and mulga grass are relatively thin and raindrops can therefore readily penetrate through them, undergoing very little change in energy. Secondly, the distribution of basal cover provided by the tussocks of these plants is very patchy, with often only 2–3 plants/m^2 in the quadrat. Such a sparse distribution of basal cover is probably highly inefficient at reducing the detachment of sediment.

It is probable that both of the above factors contribute to the non-significant effect of cover on sediment concentration in our experiments. Other experiments under rangeland conditions have also shown a non-significant effect of cover on erosion (Simanton *et al.* 1991). However, it is important to note that our results are only from 1 m^2 plots, and further work is needed to scale these findings up to a paddock scale. The above results also illustrate the importance on cover configuration on erosion processes. Further work in this area is currently in progress (P. Hairsine, pers. comm.).

In addition, in our experiments, it is possible that an increase in erosive stress may result from the decrease in the flow depth (Kinnell *et al.* 1990) caused by the increase in the infiltration rate with cover. However, using the recession curves, it was possible to estimate that the mean flow depth was $1{\cdot}2{\pm}0{\cdot}2$ mm and that this depth was independent of cover. It should be noted that because the infiltration rate does not in fact remain constant during the recession, there is a potential for this method to overestimate flow depth. However, this may, to some extent, be offset by the failure to consider depressional storage in the calculation of mean flow depth.

Direct Effects of Grazing on Runoff, Soil Physical Properties and Sediment Concentration of Bare Soil

Runoff and soil physical properties

Fig. 3 shows that at zero cover there was very little difference in the runoff rate (and infiltration rate) measured with the rainfall simulator between the high and low stocking rates. Soil hydraulic properties measured with the disc permeameter on bare soil 2–3 m away from tussocks also showed no significant effect of stocking rate on final infiltration rate, sorptivity and saturated hydraulic conductivity (Table 4). Table 3 also shows that there was no difference in bulk density between the two stocking rates.*

These results are not surprising given the relatively low stocking rates used and the fact that the soil surface is dry most of the year. Also, because the bare soil surface away from grass tussocks on the runoff zones already has a dense seal and poor hydraulic and physical properties (Greene 1992), it is probable that additional changes to soil hydraulic and physical properties by grazing would be minimal. Table 4 shows that after 4–5 years grazing, the soil hydraulic properties (steady state infiltration rate, sorptivity and saturated hydraulic conductivity) are very similar to the values measured at the start of the grazing trial in 1986 (Greene 1992). This is the case for both the high and low stocking rates. Dadkhah and Gifford (1980) also showed that when a clay loam surface was already badly compacted by high grazing pressure, additional trampling had little effect on infiltration rates.

The above results are in marked contrast to other studies that have shown significant effects of grazing on soil physical properties. For example, Willatt and Pullar (1983) showed that, on a poorly drained silty loam soil in southern Victoria, an increase in stocking rate increased the bulk density of the 0–60 mm layer and decreased the hydraulic conductivity. Proffitt and Bendotti (1994) also demonstrated on a fragile, sandy clay loam soil in Western Australia that grazing can reduce infiltration rates. However, both these studies have been carried out using considerably higher stocking rates (7–22 sheep ha^{-1}) and under wetter conditions where deterioration of soil physical properties is likely to occur.

The high correlation between the organic carbon content and aggregate stability of the 0–20 mm depth of soil found with the wet-sieving technique demonstrates that organic matter plays an important role in stabilizing these soils. This result is typical for red earth soils. Greene and Tongway (1989) suggested that soil polysaccharides and humic substances in soil organic matter are absorbed by soil mineral particles and assist with the formation and stabilization of aggregates. Sullivan (1990) has suggested an alternative mechanism by which soil organic matter can stabilize soil aggregates. He suggested that the hydrophobic properties of soil organic matter can increase the amount of air encapsulation during water uptake and that this encapsulation can reduce uptake rates sufficiently to prevent slaking. However, regardless of which method is operating, the net effect of organic matter is in stabilizing soil aggregates.

Sediment concentration

Table 2 shows that the sediment concentration produced by the higher stocking rate was significantly greater than that produced by the lower stocking rate, i.e. $0\cdot253\ g\ L^{-1}$ compared with $0\cdot161\ g\ L^{-1}$. This is also consistent with the higher stocking rate producing an expected greater rate of sediment loss (Fig. 5). Higher sediment concentrations and greater rates of sediment loss for areas

* It is interesting to note that the final steady state infiltration rates measured on bare soil with the disc permeameter were considerably higher than those measured with the rainfall simulator. In the case of the rainfall simulator, raindrop impact and overland flow effects cause rearrangement of particles at the soil surface and result in the formation of a rain-induced crust that has a lower infiltration than the soil surfaces associated with the disc permeameter (Greene 1993).

of higher stocking rate are to be expected, and are probably associated with greater trampling and detachment of particles from dry soil by hooves. The higher stocking rates would also cause greater depletion of organic matter and concomitant lower aggregate stability in the upper 0–20 mm soil layer.

If the material detached by hoof action remained on the soil surface the graph of cumulative sediment concentration against time would not be linear, except at the beginning of the runoff. This is because any detached material would be lost from the surface soon after runoff occurred. Probably what occurs is that the material loosened by hoof action becomes re-aggregated back into the surface soil matrix by subsequent light showers of rainfall, only to be re-eroded during simulated rainfall.

Andrew and Lange (1986) also showed that, with an increase in stocking rate, the greater hoof activity will cause more particle detachment to occur at the surface soil and hence more erosion. This effect of hoof activity increasing erosion by causing detachment, or pulverization, of soil particles from the surface of bare soil is one of the major direct impacts of grazing on red earth soils in this landscape.

Effects of Natural Rainfall on Surface Soil Conditions

Even though the above results show that the pre-existing crusts (or seals) in this landscape are little affected by the direct effects of grazing (apart from losing material due to detachment/pulverization by hoof action), they are susceptible to further crusting (or sealing) as a result of high intensity rainfall. The bare soil surfaces away from grass tussocks are particularly susceptible to crusting during rain. Micromorphological and hydraulic studies of the effects of raindrop impact on surface crusting were carried out on the same runoff zones by Greene and Ringrose-Voase (1994). Their results have shown that, under both natural and simulated rainfall at 30 mm h^{-1}, the infiltration rate of the bare soil between perennial grass tussocks rapidly declined from >20 mm h^{-1} to 4–6 mm h^{-1}. They attributed this decline to raindrop impact and subsequent further crust formation. However, these crusts were shown to be cyclic in nature and, with extended periods of drying, their micromorphological and hydraulic properties gradually returned to the pre-rainfall values (Greene and Ringrose-Voase 1994).

Implications of Grazing Management on the Long-term Stability of Semi-arid Mulga Woodlands

The results in this paper show that grazing by removing perennial grasses, leads to an increase in runoff in the runoff zones. This accentuates the xeric conditions on the runoff zones and hence makes it a less favourable environment for subsequent re-establishment of plants. Also, other work (Whitford *et al.* 1992) has shown that the habitat for the soil biota is highly correlated with the supply of grasses. The soil biota, in particular the invertebrates, are important in maintaining and improving soil physical properties, especially after high energy rains have sealed the surface (Williams and Bonell 1988).

The increased runoff from the intergrove areas due to heavy grazing may result in the groves being unable to cope with the extra runoff water generated in high intensity rainfall events. Under such circumstances, excess runoff would bypass the groves and be lost out of the land system. Similarly, Perry (1970), working in mulga woodlands near Alice Springs in Central Australia, found that, for rainfall events up to approximately 25 mm, the runoff was contained in the intergrove/grove system. However, with larger or very intense events, runoff into regional drainage systems occurred. The problem of excess runoff being shed into regional drainage systems would be exacerbated if the high infiltration rates in the groves were also reduced by heavy grazing. Infiltration measurements made after approximately 7 years of grazing indicate that this has in fact occurred, with the infiltration rate down to approximately one third of the value at the start of the trial (unpublished data).

Observations in the general area surrounding the experimental site at Lake Mere indicate that, in many areas that have been extensively over-grazed, the intergrove/grove system has ceased to function (Tongway and Ludwig 1990). Therefore, grazing management, through its indirect and direct effects on the infiltration and runoff characteristics of the soils in these runoff zones, can exert a major influence on the long-term stability of the mulga woodlands.

Conclusions

The results from this study in a semi-arid mulga landscape reinforce the concept that in rangelands grazing is the major disturbing factor on soil properties. This is due to: (i) the indirect effect of grazing in defoliating the vegetation and removing cover, thereby increasing runoff, and (ii) the direct effect of the animal hoofs which compact and/or pulverize the soil surface. In addition to the effects of grazing, the bare inter-tussock areas are particularly susceptible to crusting under raindrop impact.

Furthermore, this study showed that, even though the indirect effect of grazing in removing plant cover significantly increased runoff, plant cover appeared to have no significant effect on sediment concentration. However, it is important to note that these results were obtained from 1 m^2 plots and further work is needed to scale these findings up to a paddock scale. Further work on the efficacy of other perennial grasses (besides woollybutt and mulga grass), in conducting water into the soil, should also be carried out. In particular it is important to establish if canopy cover directly affects infiltration or if the indirect effects associated with canopy cover, such as increased soil macroporosity, due to the soil biota, soil organic matter and aggregate stability, are the dominating factors.

The direct effect of hoof action, however, while not significantly compacting the soil surface (and therefore having no effect on runoff), did result in greater particle detachment and pulverization at the soil surface. This lead to a less stable surface and hence increased sediment concentration in the runoff.

Therefore, if the management of these semi-arid lands is to be sustainable, it is critical to devise tactical grazing systems that maintain adequate populations of perennial grasses and minimize surface pulverization.

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