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Bladeploughing and exclosure influence soil properties in a semi-arid Australian woodland

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Abstract

Runoff and sediment yield were evaluated on a sandplain dominated by woody perennial shrubs in north-western NSW, Australia. The site was bladeploughed; and some plots were grazed by sheep and cattle and others exclosed from grazing. Two years after ploughing and exclosure, grazed plots had significantly lower levels of aggregate stability and organic carbon compared with ungrazed plots, but there was no effect of ploughing. Surface pH levels were significantly greater on unploughed plots compared with ploughed plots. Two years after treatment, runoff and sediment yield were greatest on plots with the least disturbance (unploughed and ungrazed) and least on sites with the greatest disturbance (ploughed and grazed). We attribute differences in soil hydrology to the development of a thin physical soil crust on the unploughed-ungrazed plots, which restricted infiltration. On the ungrazed plots, increases in plant cover and biomass, and colonisation of the physical crust by biological elements, are hypothesised to lead to reduced runoff and sediment yield over time.

Key Words: rangeland hydrology, runoff, infiltration, rainfall simulation, sandplain, woody shrubs, soil crusting

Semi-arid woodlands are important range types in eastern Australia, supporting extensive sheep and cattle grazing for wool and meat production (Young 1980). Serious declines in productivity have occurred over extensive areas of woodland. This decline takes the form of depletion of palatable perennial pasture species and their replacement with less-desirable ephemerals, encroachment of inedible native shrubs onto productive grazing country, and increases in the area of bare ground and eventually soil erosion. Woody shrub encroachment has accompanied the active suppression of fire by europeans (Harrington et al. 1984). Evidence suggests that shrubs have generally been favoured, both directly and indirectly, at the expense of grasses, by inappropriate grazing management. These factors, and perhaps many others, have resulted in major increases in the density of woody shrubs. The viability of grazing enterprises has declined significantly under current management styles.

Over the past 2 decades, pastoralists, researchers, and advisers have investigated a range of treatments to control woody shrubs. These include fire (Hodgkinson and Harrington 1985), herbicides (Noble et al. 1992), grazing by goats (Torpy et al. 1992), bladeploughing (or rootploughing; Robson 1993, 1994), chopper rolling and land imprinting (Eldridge unpublished data). The Department of Conservation and Land Management (formerly the Soil Conservation Service of New South Wales) promoted bladeploughing to control woody shrubs of the genera *Dodonaea*, *Senna*, and *Eremophila* on areas of red earth soils. In 1990 the government funded a demonstration of the technique in the Bourke district of far north-western NSW. Treatment costs ranged from \$A61 to \$A98 (\$US46–74) per hectare (Robson, unpublished data). Despite the high treatment costs and the relatively low value of semi-arid rangelands (MacLeod 1993), many pastoralists have shown a keen interest in bladeploughing, and a few have invested large sums in the operation. While the effects of bladeploughing on pasture composition and dynamics is currently being investigated at 2 sites in the Bourke district, little effort has been directed towards quantifying the effect of bladeploughing on soil movement and hydrology.

In April 1991 an experiment was initiated to study the response of a semi-arid woodland to 4 treatment combinations. The combinations involved grazing and bladeploughing, both imposed at 2 levels, presence and absence. The aim was to examine the effectiveness of the various treatments in improving pastoral productivity in terms of various soil and vegetation attributes. In this paper we discuss 1 aspect of that study, where we examined soil hydrological properties, particularly runoff, and sediment yield, in each of the treatments. The effects of ploughing and grazing on pasture dynamics are discussed elsewhere (Robson 1995).

Materials and Methods

The Study Area

The trial was carried out at 'Bloodwood' Station, a grazing property of approximately 25,000 ha used mainly for sheep, but with some cattle grazing. 'Bloodwood' is located approximately 120 km north-west of Bourke in north-western New South Wales

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(144°45'E, 29°30'S). 'Bloodwood' receives a mean annual rainfall of 310 mm. Averaged over the long term, 45% more rain falls during the summer than the winter. In the 12 months preceding the experiments, the site received 221 mm of rain, of which 120 mm fell in the warmer half of the year. January is the hottest month in the region with mean temperatures of 36.4°C. Winters are mild and the coolest month is July with an average of 17.9°C. Winds, which come mainly from the south, are most prevalent and reach their greatest velocities during the warmer months from September to February. Bourke receives on average 17 frost days per year, usually between June and August.

The study site falls within the 'Goonery' landsystem (Walker 1991) and comprises sandplains of Quaternary alluvium and aeolian sediment. Slope is less than 1% and relief is about 5 m. The soils are principally calcareous red earths (Gn2.13; Northcote 1979) and sandy earths (Gn1.12) with sandy and loamy topsoils. In the U.S. Soil Taxonomy, the soil would be classified as a Haplargid (Soil Survey Staff 1975). The site is an area of semi-arid woodland dominated by the trees mulga (*Acacia aneura* F. Muell. ex Benth.), ironwood (*A. excelsa* Benth.), rosewood (*Alectyron oleifolius* Desf.), and belah (*Casuarina cristata* F. Muell.). The shrub layer comprised predominantly turpentine (*Eremophila sturtii* R. Br.) and hopbush (*Dodonaea viscosa* A. Cunn.), with puntybushes (*Senna* spp. A. Cunn ex Vogel) and native fuscias (*Eremophila* spp. R. Br). Pasture was dominated by woolybutt (*Eragrostis eriopoda* Benth.), with assorted species from the Chenopodiaceae and other ephemeral forbs.

The traditional use of the paddock on which the study was conducted has been the grazing of Merino wethers. Breeding cattle are grazed episodically when seasonal conditions are conducive. Government records indicate that the land type is rated at a stocking rate of 1 wether (DSE: dry sheep equivalent) per 4 ha. Since the treatment in 1991, the leaseholders of 'Bloodwood' have continued to graze wethers, though intermittently. From April 1991 until April 1993 the paddock was grazed at the customary rate of about 1 DSE per 4 ha. Despite the lack of empirical evidence, anecdotal and personal observations suggest that uncontrolled grazing by kangaroos and feral goats has been significant over the same periods.

At a site where *Eremophila*, *Dodonaea*, and *Senna* spp. dominated vegetation biomass, an area was selected and half was fenced (2 m high and netted) to exclude sheep, cattle, goats, kangaroos, and rabbits. The exclosure was approximately 400 m by 150 m (6 ha). Half of the exclosure (400 m × 75 m), and half of the adjacent unfenced grazed area were bladeploughed. Treatments were not randomly arranged within the block. To minimise fencing costs, the 2 exclosed treatments were put side by side. Similarly, bladeploughing logistics dictated that both bladeploughing areas were arranged next to each other.

An 89.5 kW (120 hp) crawler tractor was used to pull a single-tyned 4.2 m wide V-shaped 'Stationmaster' bladeplough. The blade was maintained at a depth of 20–30 cm below the surface in order to sever the taproots of shrubs below their lateral root systems.

Measurements

All vegetation, soil, and hydrological measurements were made on 20 plots, each of 0.84 m by 0.84 m. This represented 5 plots from each of the 4 treatments i.e. ploughed-grazed, ploughed-ungrazed, unploughed-grazed, and unploughed-ungrazed. Within each treatment, the 5 plots were stratified within inter-shrub sites to represent the range of cover and biomass levels of grasses and ephemerals present when the rainfall simulations were made. Mean pre-simulation values of plant cover, biomass, soil moisture and microtopography are given in Table 1. Former shrub coppice areas were avoided. Plots on ploughed treatments were all aligned along the direction of ploughing. All measurements were made in April 1993, 24 months after bladeploughing.

Soil Surface Microtopography

Prior to rainfall simulation, soil microtopography was measured on top of each runoff plot using a profilemeter (Semple and Leys 1987). This measures along a row of 16 vertical steel rods spaced at 50 mm intervals. Ten rows were used, spaced 90 mm apart. The profilemeter measured microtopography perpendicular to the direction of ploughing, after the ends of each of the pins came into direct contact with the soil surface. The vertical position of each pin was measured to the nearest 1 mm. Microtopography was expressed as the standard deviation of the 160 pins.

Soil Physical Properties

The stability of dry soil aggregates was used as an index of erodibility of the 'Bloodwood' soils using a field-based dry sieving technique (Semple and Leys 1987). This was used because it was felt that a traditional wet sieving approach (Greene 1992) would have overinflated the erodibility of these soils, given their low silt and clay contents (15.1–23.0%, Table 2). Furthermore,

Table 1. Mean pre-simulation values of soil moisture, microtopography, biomass and cover of pasture, cryptogams and litter for the 4 combinations of ploughing and grazing. Means values within a row followed by a different letter are significantly different at P=0.05. Only significant differences are indicated.

	Ploughed				Unploughed			
	Grazed		Ungrazed		Grazed		Ungrazed	
	mean	se[1]	mean	se	mean	se	mean	se
Soil moisture (%)	1.02	0.08	0.97	0.09	1.22	0.07	1.06	0.19
Microtopography (mm)	1.894[a]	0.479	1.286[a]	0.260	0.827[b]	0.173	0.777[b]	0.220
Pasture biomass (g)	3.5[a]	0.7	107.7[b]	42.3	25.1[c]	15.4	98.9[b]	98.9*
Ground cover (%)								
Pastures	1.3[a]	0.66	27.5[b]	7.72	1.4[a]	0.59	4.8[a]	1.99
Cryptogams	0.0[a]	0.0	0.5[a]	0.5*	3.8[b]	2.44	12.7[b]	8.69
Litter	8.0	8.0	16.3	5.94	10.9	5.66	3.6	1.74

[1]Standard error of the mean
*Data from a single plot only

Table 2. Particle size analyses from 2 depths (0-20 mm and 20–40 mm) from each of the 4 combinations of ploughing and grazing. Means values within a row followed by a different letter are significantly different at P=0.05. Only significant differences are indicated.

	Ploughed				Unploughed			
	Grazed		Ungrazed		Grazed		Ungrazed	
	mean	se[1]	mean	se	mean	se	mean	se
0-20 mm								
Clay (<0.002mm)(%)	12.7	2.51	18.0	2.01	14.5	1.75	14.3	2.33
Silt (0.02–0.002mm)(%)	2.4	1.25	5.0	0.89	5.0	1.10	3.6	1.21
Fine sand (0.2–0.02mm)(%)	61.1	2.63	59.4	2.80	60.1	4.01	63.9	6.91
Coarse sand (0.2–2.0mm)(%)	23.8[a]	1.47	17.6[b]	0.60	20.4[a]	1.43	23.0[a]	1.46
20-40 mm								
Clay (<0.002mm)(%)	12.7	1.95	14.6	1.91	15.4	1.93	17.0	2.80
Silt (0.02–0.002mm)(%)	2.6	1.29	6.3	2.33	4.8	0.86	4.2	1.28
Fine sand (0.2–0.02mm)(%)	60.5	2.77	61.4	3.41	61.5	5.08	55.8	2.21
Coarse sand (0.2–2.0mm)(%)	24.2[a]	1.15	17.8[b]	0.72	18.4[b]	2.66	23.1[a]	1.59

[1]Standard error of the mean

the technique needed to be performed in the field as transportation of samples to the laboratory approximately 550 km from 'Bloodwood' would likely have shattered soil aggregates and masked any effects of the various factors. Approximately 2,000 g of soil from the top 20 mm was sieved through a 0.84 mm sieve. The percentage of soil 2.00–0.84 mm was used as an index of erodibility.

Gravimetric soil moisture measurements were taken adjacent to the plots before simulation in the 0–20 mm and 20–40 mm layers. Other soil physical properties were measured according to the following methods:

(i) pH and electrical conductivity (EC): 1:5 soil water suspension shaken for 1 hour.

(ii) organic carbon: Walkley-Black wet combustion (Colwell 1969).

(iii) particle size analysis on the <2 mm fraction after Loveday (1974) using dispersed samples.

Vegetation

Foliage cover of the vegetation (aerial hit) and basal cover of various cover components (ground hits) were measured at the same pin locations as microtopography (Table 1). Basal cover data were recorded in the following categories: bare soil, litter, cryptogams, perennial grasses, perennial forbs, and ephemerals. The cryptogam category comprised cyanobacteria (blue-green algae), crustose lichens, and some mosses. Above-ground plant biomass (standing dead plus live, and litter) was determined by clipping all of the vegetation after rainfall simulation and weighing after oven-drying at 65°C for 48 hours.

Rainfall Simulator Measurements

A revolving disc rainfall simulator (Grierson and Oades 1977) was used to apply rainfall to the 20 plots. On level terrain the simulator nozzle is calibrated to deliver raindrops from a standard height of 2.05 m, producing rainfall of 2.5 mm diameter mean drop size with energy of approximately 30 kJ m^{-2} min^{-1} using 52 kPa pressure. By varying the disc aperture on the simulator, we calibrated the nozzle to deliver 45 mm $hour^{-1}$ while level. However, on some plots, which varied slightly in local topography, the need to keep the simulator level meant that rainfall intensity varied slightly among plots. The average rainfall intensity of 47 mm $hour^{-1}$ rainfall intensity on any plot varied between 44.1 mm $hour^{-1}$ and 49.2 mm $hour^{-1}$ (s.d.± 1.66 mm $hour^{-1}$). Rainfall was applied at a constant rate until steady-state runoff was achieved, usually within 30 to 45 minutes.

Time to ponding and time to runoff were recorded for each plot after commencement of rainfall. Time to ponding is defined as the time taken from initiation of rainfall for standing water to cover 60% of the soil surface. Whilst this method may appear subjective, comparisons with the tensiometer method indicates no appreciable differences between both methods (I. Packer, unpublished data). Furthermore, our technique of estimating time to ponding means that there is no disturbance to the soil surface, which would otherwise occur when using tensiometers. Time to runoff is defined as the time from commencement of rainfall when runoff first appeared in the collecting trough. The mean depth to the wetting front was measured at the cessation of simulation at 10 locations on each plot. Wetting front is expressed as a depth per 25 mm applied rainfall in order to standardise wetting front depths between plots receiving slightly different amounts of rainfall.

Runoff and Sediment Yield

Each runoff plot was bordered by sheet steel buried 5 cm into the soil and rising 10 cm above the soil. This prevented water from leaving the plot and was high enough to prevent water falling outside the plot from entering the measuring flume. Runoff was collected in a flume at the lower end of the plot. The flume was constructed so that runoff and sediment would enter from upslope but rainwater was prevented from entering directly from above. Once time to runoff had occurred, the vacuum pump at the base of the flume was activated and runoff and sediment was pumped into a graduated measuring cylinder and the heights recorded at 1 minute intervals. At 5 minute intervals, runoff samples were bulked and retained for determination of sediment yield. The weight of sampled sediment was determined after drying at 105°C for 24 hours. Sediment collected from the plots represents the total contribution from rainsplash and flow-driven erosion processes. Sediment yield was expressed as oven dry soil per 25 mm applied rainfall per m^2, and average sediment concentration as sediment yield per litre of runoff.

Analyses

Differences in the independent variables between the 4 ploughing-grazing factors were determined using two-way analysis of variance (Minitab 1986). Data were transformed ($sine^{-1}$ or square root) to stabilise the variances before ANOVA was performed. Simple linear regression was used to examine the contribution of the various independent variables to the variance in the dependent variables, after stabilising the variances and testing for normality (Minitab 1986).

Results and Discussion

Soil Physical Properties

The effects of ploughing and grazing are reflected in the soil physical and chemical properties of the surface soils. There were significant differences in the coarse fraction of the soils among the 4 treatments (Table 2). Soils at the ungrazed sites at both depths contained significantly lower levels of coarse sand on the ploughed plots compared with the unploughed (P=0.05). At the grazed sites however, coarse sand fractions were significantly greater on the ploughed soils. This relative increase in coarse particles results from a preferential sorting of the finer particles from the surface of the grazed soils. Whilst this preferential sorting of material is consistent with the data for the 20–40 mm depth, variability around the mean value means that no statistical significance can be attached to the results for the 0–20 mm depths (Table 2).

Organic carbon levels were greater in the ungrazed soils compared with the grazed, though only significantly at the 20–40 mm depth (Table 3). Organic carbon levels are known to be low in Australian soils (Stafford Smith and Morton 1990). Studies near Cobar, approximately 150 km south of 'Bloodwood' have demonstrated reductions in organic carbon levels of 32% on eroded soils with poorer range condition, purportedly due to heavier grazing (Noble and Tongway 1986). Soil pH from surface soils (0–20 mm) was significantly higher on the unploughed sites compared with the ploughed sites ($F_{1,16}$=7.555, $P<0.05$). The effects of increases in pH on soil hydrology or even plant growth are unknown. There were no significant differences in electrical conductivity at either the 0–20 mm or 20–40 mm depths (Table 3).

Dry aggregate stability was significantly higher in the ungrazed treatments compared with the grazed treatments ($F_{1,16}$=14.29, $P<0.01$), but there were no significant differences between ploughed and unploughed plots (Table 3). One or more of the following factors may explain these results: Firstly, even in the presence of cattle and sheep grazing, soil aggregation was either unaffected by ploughing, or re-established to levels similar to the control plots (unploughed) within 2 years of ploughing. Secondly, exclosure for only 2 years, even after ploughing, was sufficient to restore aggregate stability levels to the level found on the control plots (74–81%, Table 3).

Times to Ponding and Runoff, and Depth to Wetting Front

The hydraulic responses of a soil can be described by the time taken for water to pond on the surface (TP), the time elapsed before runoff occurs (TR) and the depth to which infiltration water reaches into the soil profile (WF). Time to ponding occurs when the capacity of the soil surface to absorb water is exceeded by the delivery rate or rainfall rate. The time taken for runoff to occur once rainfall has ponded on the surface depends principally on surface roughness or detention. The depth to wetting front is most strongly influenced by porosity, with large pores (macropores) increasing the depth to which the water will penetrate through the profile.

Time to ponding, time to runoff and depth to the wetting front all increased with the degree of disturbance, i.e. were least on the unploughed-ungrazed plots and greatest on the ploughed-grazed plots (Table 4). Time to ponding and time to runoff were significantly greater on the grazed compared with the ungrazed plots ($F_{1,16}$=6.118 and 8.556, $P<0.05$, and 0.01 respectively). Despite some major differences in these hydrological properties, the high variability around the mean values leads to no significant effects of ploughing.

There were however, significant effects of both ploughing and grazing on the depth to wetting front (Table 4). Grazing resulted in increased depths to penetration of water ($F_{1,16}$= 8.778, $P<0.01$). Similarly, as might be expected, ploughing resulted in increased penetration of water ($F_{1,16}$ = 9.102, $P<0.01$). Ploughing these soils would have created fine fissures and cracks in the soil allowing infiltrated water to reach lower into the profile.

Regression analyses revealed significant relationships between soil and vegetation attributes, and time to ponding (TP), time to runoff (TR) and depth to wetting front (WF), though only on

Table 3. pH, electrical conductivity and organic carbon from 2 depths (0-20 mm and 20-40 mm), and dry aggregate stability from the 0-20 mm depth for the 4 combinations of ploughing and grazing. Means values within a row followed by a different letter are significantly different at P=0.05. Only significant differences are indicated.

	Ploughed				Unploughed			
	Grazed		Ungrazed		Grazed		Ungrazed	
	mean	se[1]	mean	se	mean	se	mean	se
pH (water)(1:5)	5.3[a]	0.11	5.8[a]	0.23	6.2[b]	0.26	6.3[b]	0.34
EC (dS/m)	0.022	0.002	0.022	0.002	0.030	0.005	0.026	0.009
Organic carbon (%)	0.266	0.04	0.346	0.043	0.348	0.039	0.420	0.077
Dry aggregate stability (>0.84mm)(%)	57.5[a]	7.22	74.2[b]	4.00	57.9[a]	6.52	80.7[b]	2.28
Microtopography (mm)	1.894[a]	0.479	1.286[a]	0.260	0.827[b]	0.173	0.777[b]	0.222
20-40 mm								
pH (water)(1:5)	5.6[a]	0.24	5.6[a]	0.26	6.1[b]	0.34	6.1[b]	0.58
EC (dS/m)	0.024	0.004	0.030	0.006	0.038	0.010	0.044	0.020
Organic carbon (%)	0.237[a]	0.017	0.372[b]	0.050	0.285[a]	0.043	0.466[b]	0.012

[1]Standard error of the mean

Table 4. Time to ponding (TP), time to runoff (TR), depth to wetting front (WF) and steady state runoff (SSR) for the 4 combinations of grazing and ploughing. NS indicates not significant at P<0.05, * indicates significant at P≤0.05, ** indicates significant at P<0.01.

Treatment		TP mean	TP se[1]	TR mean	TR se	WF mean	WF se	SSR mean	SSR se
		(min)		(min)		(mm/mm rain)		(mm/hr)	
Ploughed	Grazed	10.65	4.05	13.58	4.19	181.0	26.66	15.6	5.42
	Ungrazed	2.28	0.31	4.42	0.57	85.4	22.9	42.6	5.93
Unploughed	Grazed	3.05	1.18	6.66	0.89	86.4	3.54	32.6	9.03
	Ungrazed	1.79	0.47	3.34	0.51	45.8	9.26	40.6	9.91
Grazing effect		$F_{1,16}$=6.118*		$F_{1,16}$=8.556**		$F_{1,16}$=8.778**		$F_{1,16}$=6.387*	
Ploughing effect		NS		NS		$F_{1,16}$=9.102**		NS	

[1] Standard error of the mean

unploughed plots. On the unploughed-ungrazed plots, time to ponding was positively correlated with microtopography (r=0.94, P=0.018) but negatively correlated with the percentage of soil aggregates >0.84 mm (r=–0.92, P=0.025). Time to runoff were positively correlated with microtopography and foliage cover (r=0.88 and 0.90 respectively, P=0.049), and depth to wetting front was positively correlated with microtopography (r=0.89 P=0.042). On the unploughed-grazed plots both time to runoff and depth to wetting front increased with increases in cover of perennial forbs (r=0.93 P=0.022 and r=0.90, P<0.036 respectively).

Runoff

Given the markedly greater pasture biomass in the general area on the ungrazed plots (450 kg ha^{-1}) compared with the grazed plots (160 kg ha^{-1}, Robson unpublished data), we expected lower runoff rates from these plots. However, runoff was markedly greater on the ungrazed plots ($F_{1,16}$= 6.387, P<0.05) which also had greater

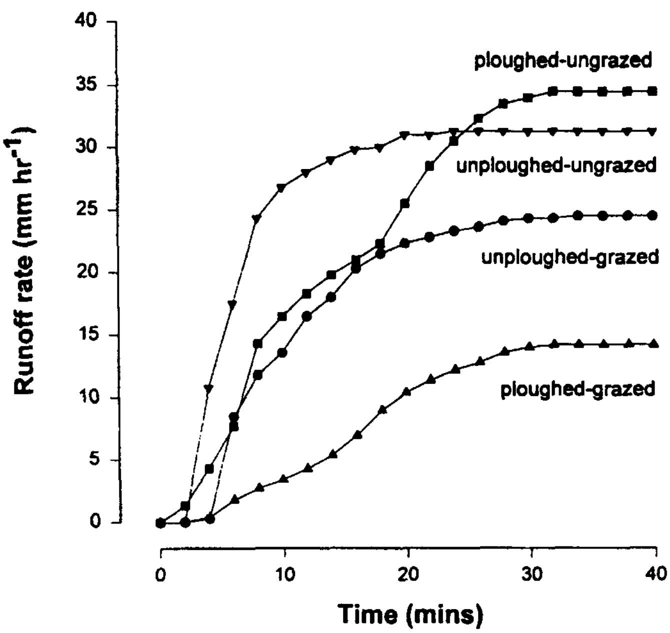

Fig. 1. Runoff curves for plots from the 4 combinations of ploughing and grazing under an applied rainfall of 47 mm hr^{-1}. Curves are averaged over the 5 plots in each treatment.

vegetation cover (Table 1). Plots with the least disturbance, i.e. the unploughed-ungrazed plots, had the highest runoff rates (Fig. 1). During the initial 25 minutes of simulations, runoff was significantly greater on the unploughed-ungrazed plots compared with the ploughed-grazed plots (Fig. 1). However, during the final 15 minutes of simulations, rates on the ploughed-ungrazed plots were slightly greater than that on the unploughed-ungrazed plots. The ploughed-grazed and unploughed-grazed plots had runoff rates intermediate between the 2 extremes (Fig. 1).

Increasing the degree of disturbance from unploughed-ungrazed to ploughed-grazed generally increased the time taken to achieve steady-state runoff. For example, the unploughed-ungrazed plots attaining equilibrium at 20 minutes compared with 30–32 minutes for the ploughed-grazed plots (Fig. 1).

Reductions in runoff after shrub control have been observed in studies in other semi-arid rangelands. Richardson et al. (1979) showed that rootploughing a honey mesquite (*Prosopis glandulosa*) stand in the Sonoran Desert in Texas reduced runoff by about 20% over a 10 year period. This was attributed to the mechanical disturbance of the soil, creating large depressions and providing entry points into the soil through the shattering of the limestone substrate. However, ploughing of honey mesquite shrubs on the Blackland Prairie near Texas, increased runoff by about 10% (Richardson et al. 1979).

Compared with the grazed plots (both ploughed and unploughed), increased runoff rate on the ungrazed plots could have resulted from 1 or more of the following: i) a lower infiltration capacity on the ungrazed soils, ii) lower interception capacity of plants on the ungrazed soils, iii) reduced microrelief resulting in less surface detention and reduced infiltration on the ungrazed soils, and/or iv) increased crusting on the ungrazed soils due to differences in plant cover or reduced soil disturbance. These 4 factors are discussed below in relation to their effect on runoff.

a) Infiltration capacity: There is no reason to expect major differences in infiltration capacity between the extreme treatments, i.e. the ploughed-grazed and unploughed-ungrazed plots, as the site on which the study was established received the same grazing treatment prior to ploughing and fencing. In the short-term, some differences in infiltration capacity could be expected on the residual hummocks after shrub removal, due to differences in shrub and intershrub soils. Soils under shrubs might be expected to have higher levels of favourable soil physical properties such as aggregate stability and macroporosity, though this was not evident in our study (Table 3). Alternatively, the presence of preferential flow paths generated by rootholes, macrofaunal burrows, and interpedal spaces between large soil aggregates stabilized by organic matter would be expected to enhance infiltration (Branson et al. 1981, Eckert et al. 1986, Dunne et al. 1991).

b) Interception capacity: Although data on the contribution of grasses and forbs to interception storage are unavailable, our field observations suggest that interception capacity was small compared with the large volume of water applied to the plots. We believe therefore that differences in runoff were not due to any changes in interception capacity.

c) Surface roughness: Although we found no significant effect of grazing on soil surface roughness (microtopography), ploughed plots were significantly rougher than unploughed plots ($F_{1,16}$ = 8.48, P<0.025). Microtopography on unploughed plots averaged 0.802 mm compared with 1.590 mm on ploughed plots (Table 1). Whilst some plots may have ponded more water through increased sites for rainfall detention, regression analyses failed to detect any significant effects on runoff. However, on the unploughed-ungrazed plots, microtopography was highly correlated with time to ponding, time to runoff and depth to wetting front (r> 0.85; P<0.50). Differences in microtopography caused by ploughing would probably be short-lived, due to redistribution of soil material by both wind and water erosion, though this would depend on the frequency of wind erosion events. Although data on water erosion in the immediate area are unavailable, in a similar sandy environment, Leys (1992) measured wind erosion of 6780 kg ha^{-1} min^{-1} from a 75 km hr^{-1} simulated wind storm. Whilst the data of Leys (1992) are from a highly erodible dune system, they demonstrate the potential magnitude of wind erosion on sandy soils in the region.

d) Soil crusting: Well-developed physical soil crusts were present on the surface of many plots, particularly the ungrazed (unploughed and ploughed) plots. These discontinuous crusts, which occurred in patches of <1 m^2 in area, were typically <1 mm thick and overlain by a thin layer of redistributed sand grains. These sand grains probably represent saltated material detached during previous wind erosion events. Greene et al. (in press) contend that the presence of iron-stained clay coatings on these sand grains indicates that erosion has not occurred for some time. In many areas, the crust comprised filaments of *Scytonema* or *Nostoc*, ubiquitous cyanobacteria of semi-arid areas which have the capacity to fix atmospheric nitrogen (Eldridge pers. observ.).

Whilst crust cover was greatest in the ungrazed areas (mean cover 25.6%), they also occurred on the grazed plots (7.9%). The significantly reduced cover levels was presumably due to trampling by sheep and cattle. The type of surface crust varied over short distances and biological crusts (cryptogams) were found adjacent to physical crusts. Different infiltration rates on similar soils in close proximity have been attributed to differences in the proportions of the various crusts (Greene and Ringrose-Voase 1994).

Our observations during rainfall simulations suggest that these crusts maintain their integrity under rainfall intensities of 47 mm $hour^{-1}$, providing that the surface is undisturbed. Outside the exclosure. Trampling by cattle on the grazed plots destroyed the majority of the crust, allowing water to infiltrate and therefore reducing runoff. On similar soils on a dunefield land system near Cobar, New South Wales, removal of the physical soil crust from the dune flank delayed the onset of runoff by 1 hour. When runoff occurred, it was significantly less than that on the undisturbed crust (Greene et al. in press). Similarly removal of a thin (<2 mm thick) biogenic crust dominated by cyanobacteria, from the surface of a sandy dune soil in the western Negev reduced any chances of runoff generation (Yair 1990). The cyanobacterial sheaths in these crusts are thought to repel water thereby retarding infiltration.

Although removal of the crust reduced runoff in the short-term, the loosely-packed sand grains undergo further sealing under raindrop action unless protected by vegetation. Thus management strategies which encourage the destruction of the crust in order to improve infiltration and seedling establishment (Savory 1988), will prevent long-term stabilisation of the surface by biological crusts or ephemeral and perennial plants.

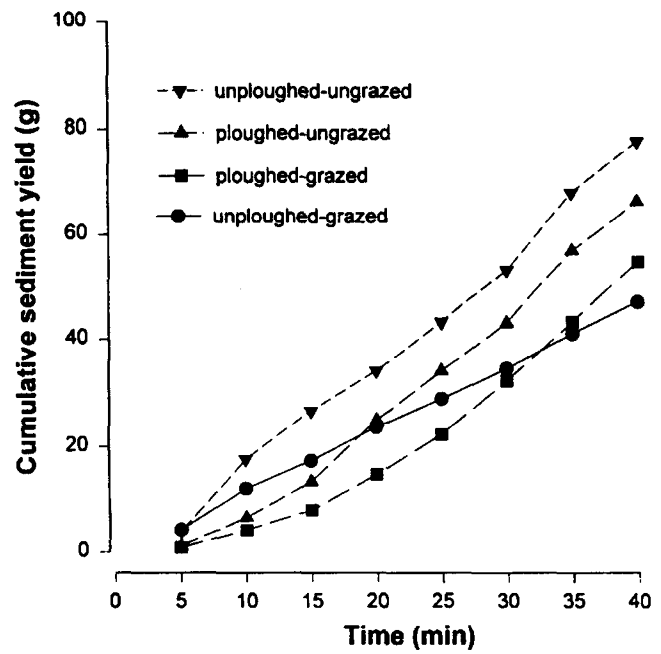

Fig. 2. Cumulative sediment yield curves for plots from the 4 combinations of ploughing and grazing.

Sediment Yield

Trends in cumulative sediment yield over the 40 minutes of simulations are given in Fig. 2. Final cumulative sediment yield ranged from 47.0 g on the unploughed-grazed plots to 77.8 g on the unploughed-ungrazed plots (Table 5). Sediment yield on the unploughed-ungrazed plots was significantly greater than that on the ploughed-grazed plots, but there were no significant differences among the other treatments.

On the ploughed-grazed plots, sediment yield was positively correlated with percentage of organic carbon in the surface 20 mm of the soil (r=0.94). Sediment concentration (g $litre^{-1}$ of runoff) was negatively correlated with foliage cover and cover of perennial forbs (r=-0.88 and –0.98 respectively).

Over time, runoff and sediment yield are likely to change as the nature of the pasture and soil crust changes. For example, where grazing is excluded, the physical crust, analogous to that described by Yair (1990) is likely to become colonised by biological elements to form a microbiotic crust (Scott 1982). Studies at Yathong Nature Reserve in central western New South Wales have shown that well-developed crusts, with a rich association of

Table 5. Runoff, sediment yield and sediment concentration from the 4 combinations of ploughing and grazing.

Treatment	Runoff		Sediment Yie ld		Sediment concentration	
	mean	s.d.	mean	s.d.	mean	s.d.
	(Liters)		(g)		(g/L)	
Ploughed-grazed	3.83	1.42	54.70	8.20	46.70	28.70
Ploughed-ungrazed	11.03	1.79	66.40	16.40	7.41	6.28
Unploughed-grazed	9.38	5.21	47.00	29.50	5.40	2.06
Unploughed-ungrazed	12.63	2.03	77.80	3.82	7.11	3.53

lichens and mosses, are associated with areas of higher infiltration (Eldridge 1993) and reduced sediment yield (Eldridge and Greene 1994).

Associated with an increase in the biological component of the surface is an increase in the growth of perennial grasses such as *Eragrostis eriopoda* Benth. and *Stipa* spp. and an increase in soil macroporosity. Studies in other semi-arid woodlands have shown that in areas excluded from grazing for 15 years, soil macroinvertebrates rapidly increase levels of aggregate stability and macroporosity, resulting in high infiltration capacity, and lower runoff and sediment yield (Eldridge and Rothon 1992).

These hypothesised temporal changes in runoff and sediment yield are consistent with observations in the Chihuahuan Desert following rootploughing of creosote bush (*Larrea tridentata* Sesse & Moc. ex. DC.). In their experiments, Wood et al. (1991) found that sediment yield was lower on the rootploughed plots during the first 12 months after treatment, but greater during the second year. Three years after treatment however, both runoff and sediment yield were less on the rootploughed areas. These results are consistent with an increase in plant establishment, often on hummocks occupied by former shrubs, possibly due to the reduction in competition for water and nutrients.

Conclusions

Our results suggest that bladeploughing (and the consequent removal of woody shrubs) and grazing lead to increased water infiltration and reduced runoff and sediment yield, at least in the short-term.

Predictions about the long-term effects which ploughing and continued grazing might have on soil properties should however be made with caution. The runoff rates and sediment yields measured in this study appear to be quite anomalous when contemporaneous pasture biomass data taken from the same plots are considered. Robson (1995) found substantially more perennial pasture in the 2 ungrazed treatments (which exhibited greatest runoff rates and sediment yield) than the 2 grazed treatments. Moreover, ploughing only advantaged pasture when grazing had been removed afterwards.

Evidence suggests that improved soil hydrology is normally correlated with increased vegetation biomass and soil biological activity. It is reasonable to expect that the differences in soil physical properties which currently exist between the treatments could change significantly in the future.

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