

## Effects of sheep grazing episodes on sediment and nutrient loss in overland flow

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**Abstract.** The effect of sheep grazing on the loss of sediment and nutrients in overland flow was investigated on a hill-country farm in the Waikato, New Zealand. The losses were measured in runoff produced artificially with small (0.5 m<sup>2</sup>) and large (1050 m<sup>2</sup>) rainfall simulators. Immediately after intensive winter grazing, rainfall applied at high intensity increased concentrations by a factor of 13–16 for sediment and particulate nutrients, 33–76 for dissolved reactive phosphorus and ammonium-nitrogen, and 5–7 for dissolved organic nitrogen and phosphorus. During summer, when there was less removal of vegetative cover, there was a smaller effect of grazing. The concentrations of sediment and particulate nutrients in overland flow were strongly correlated with the percentage of bare ground. The concentrations returned to background levels within 6 weeks after grazing, and the infiltration rate and ground cover also recovered from grazing in this time. The small rainfall simulator experiments showed that the infiltration rate decreases with grazing, which results in greater runoff after grazing. The greater runoff combines with the increased concentrations to give higher loads after grazing. In late winter, the infiltration rates were approximately half the summer values and the soil erodibility was approximately double, so the risk of high sediment and nutrient loads is greatest in winter, especially considering the higher rainfall and lower grass growth. The management implications are that exposure of bare ground associated with intensive grazing should be avoided, especially in winter.

*Additional keywords:* erodibility, infiltration, rainfall simulator, treading, hillslope.

### Introduction

Intensive grazing by sheep results in damage to pasture, which increases the concentration of sediment and nutrients in overland flow and the amount of runoff generated. This has the potential to degrade water quality in streams and increase the contaminant load to lakes and estuaries. There is a need to quantify such effects to enable improved management of pasture. The sediment load from hillslope pasture may be small compared with other sources (e.g. mass movement, streambank erosion, gully erosion). Nevertheless, we are interested in sediment loss from surface erosion in pasture because the surface soil is enriched in nutrients and pathogens.

Previous studies have assessed the effect of sheep grazing on contaminant losses in overland flow. McColl and Gibson (1979b) collected overland flow from hill pasture and found that, with the exception of nitrate, nutrient concentrations in runoff increased immediately as a result of grazing and then declined in succeeding events. The half-life for reduction in concentration (recovery) following the cessation of grazing was 23 days for total P and 8–26 days for total Kjeldahl

nitrogen (TKN). Nitrate did not increase immediately after grazing but did over the following weeks, presumably as a result of conversion of TKN to nitrate. Grazing also resulted in increased volumes of runoff (McColl and Gibson 1979a), and this was attributed to the effects of trampling of the ground. It took 8 weeks for the infiltration rates to recover.

Smith (1987) showed a strong inverse relation between the grass length and sediment and particulate nutrient concentrations for a sheep pasture in the Waikato, which suggests that removal of grass associated with grazing will increase the concentrations of contaminants in runoff. Studies of cattle grazing also show an effect of intensive grazing or treading on infiltration rates and contaminant losses (Sharpley and Syers 1976; Nguyen *et al.* 1998; Russell *et al.* 2001; Elliott *et al.* 2002).

In this study we examined the effect of sheep grazing, using small (0.5 m<sup>2</sup>) and large (1050 m<sup>2</sup>) rainfall simulators. Small simulators have been used in the past in New Zealand to investigate the effects of cattle grazing on infiltration and contaminant loss (Campbell 1945; Selby 1972; Nguyen *et al.* 1998; Russell *et al.* 2001; Elliott *et al.* 2002) but this is the

first time they have been used to assess the effects of sheep grazing in New Zealand. The advantages of using a rainfall simulator are that the rainfall can be applied at a controlled rate at the desired time, and the rate can correspond to infrequent rainfall events. Several years after the small rainfall simulator experiments, we used a large rainfall simulator to confirm the effects of sheep grazing at a larger spatial scale. Whereas the erosion in small rainfall simulators is dominated by rainfall impact, other processes can operate at a larger scale. The large rainfall simulator was positioned in a topographically convergent area of pasture, so there was the potential for shear-induced erosion associated with rivulets of flow and concentrated overland flow. We also measured a wider range of nutrient forms in the large simulator experiments.

The objectives of this study were to quantify the effects of sheep grazing episodes on runoff volume and contaminant concentrations in overland flow and to examine recovery in the subsequent months. We concentrated on the period shortly after intensive grazing episodes and the recovery in the subsequent weeks. We expected that the concentration of contaminants would increase as a result of grazing, due to removal of pasture cover and deposition of animal wastes. We also expected more runoff to be produced after grazing as a result of treading-related soil damage, and that all the effects of grazing would subside over a period of weeks to months. We did not investigate long-term or cumulative effects of grazing such as persistent soil compaction or changes to soil structure that might occur, for example, as a result of converting bush or scrub to pasture.

## Methods

### Study site and soils

The study was conducted in at the Whatawhata Research Centre, which is near Hamilton, New Zealand (37°48'S, 175°5'E, approx. 220 m a.s.l.). Vegetation at the site is predominantly ryegrass-clover pasture (*Lolium perenne* L. and *Trifolium repens* L.). The topography is generally steep (typically 15–35°). The average annual rainfall at the Research Station from 1952 to 1985 was 1627 mm with a seasonal variation (94 mm in January, 178 mm in June).

The soil for the rainfall simulator experiments was Kaawa Hill soil (*Ochreptic Hapludult*, USDA), which is a yellow-brown earth developed from argillite but can also incorporate or be overlain by weathered volcanic ash. It has a firm clay loam topsoil with moderately to strongly developed prismatic and nut structure (Bruce 1978). The top 75 mm of all of the soils is characterised by a high organic content (typically 15–20%), high total porosity (65–70%), high macroporosity (15–20%), and a low bulk density (0.75–1.0 g/mL) (Nguyen *et al.* 1998; Sheath and Carlson 1998).

### Small rainfall simulator

Tests with a small drip-type simulator (Boyer-Bower and Burt 1989) were conducted from July to November in 1996. Tests were performed immediately after a July grazing event, 6 weeks after grazing, and 3 months after grazing. The grazing episode consisted of 3 days of grazing with 300 in-lamb ewes weighing 55 kg in a 0.3-ha paddock. At various times during the grazing, small plot areas were caged off,

thereby establishing plots with different degrees of grazing. In the first set of tests, 25 plots were used and 20 of these were used in subsequent tests (5 were removed to reduce the number of tests in low-damage plots). The plot area was 0.5 m<sup>2</sup> (0.5 m across the slope, 1 m down the slope), and each plot was surrounded by a sheet-metal shield driven ~50 mm into the ground. These tests were conducted in an area with slopes of 12–19° and a soil Olsen P of 13.

The rainfall application rate was constant for any one run and was generally in the range of 50–70 mm/h, although on some plots a higher application rate was used in summer to ensure that runoff was generated. The rainfall was applied for 80 min, and runoff was collected each 10 min for the first 60 min. A 5-year annual recurrence interval 10-min duration rainfall intensity for natural rain at this site is 60 mm/h, and the 100-year 1-h rainfall is 44 mm/h. Thus the applied rainfall rates represent an infrequent rainfall intensity for this site. Based on droplet size measurements and fall velocity estimates, the kinetic energy of the raindrops was 5.4 J/m<sup>2</sup>.mm (Elliott *et al.* 2002), which is considerably less than 27 J/m<sup>2</sup>.mm expected for natural rain of this intensity (based on intensity–energy relationships developed for the USA, Wischmeier and Smith 1978; similar relations have not been established for New Zealand). The samples from a run were bulked together and the concentrations of suspended solids, total phosphorus, and total Kjeldahl nitrogen were measured. The infiltration capacity was determined from the measured runoff rate from 60 to 80 min, after which time the infiltration rate had reached a steady-state. The amount of bare ground and damage to the ground were also measured for each test, using methods described in Nguyen *et al.* (1998). The methods involved examining the vegetation and ground condition under a grid of points laid over the plot. Damage includes ground compression, hoof indentation, skidding, ridging, clodding, and puddling.

### Large rainfall simulator

Experiments with the large rainfall simulator were conducted in December 2001 and June–July 2002. Tests were performed before and after intensive grazing, in summer and in winter. The large simulator had 13 rainfall stands at 9 m spacing. Each stand consisted of a 5-m-high pole with 4 closely spaced upward-spraying sprinklers mounted on a frame at the top, to give a total of 52 sprinklers. The area of rain application was 1050 m<sup>2</sup>, although only 970 m<sup>2</sup> was in the catchment of the outlet weir. Rain was applied at 35 mm/hr over 1 h, which corresponds to approximately an 8-year recurrence interval. To ensure comparable antecedent moisture conditions, the rainfall simulator was run 1 day prior to each test to wet the soils if necessary.

Gardena Polo 220 oscillating sprinklers (obtained from NYLEX New Zealand) were used as they have a wide application area and a droplet size distribution close to that of natural rain. The sprinkler arms consist of a slightly curved 10-mm-diameter tube with 1.1-mm holes which is rotated around its long axis by a water-driven gear pump. The angle of oscillation was adjusted to give a square spray pattern. The sprinklers were operated at a pressure of 200 kPa at the sprinkler head. Water obtained from a stream on the farm was filtered through a 5-µm polypropylene filter and stored in plastic tanks for use in the simulations.

The median droplet diameter (by volume) as measured using the flour pellet method (Laws 1941) was 2.4 mm, compared with ~2.3 mm for natural rain of 35 mm/h (Laws and Parsons 1943). The variation in droplet sizes also matched natural rainfall closely, with a 10-percentile diameter of 1.5 mm and a 90-percentile diameter of 3.4 mm. The kinetic energy of the raindrops, calculated using the measured droplet size distribution and fall velocities from Laws (1941) with a fall height of 6 m, was 25.7 J/m<sup>2</sup>.mm, which is comparable to that expected for natural rain at 35 mm/h (Wischmeier and Smith 1978). The Christiansen uniformity coefficient (Christiansen 1942) for tests with no wind was 88%.

The simulator was set up in a topographically convergent area in Paddock 6 of the Whatawhata fertiliser trial area, which had a mean local slope of 17.7°. These tests were not in the same paddock as the small rainfall simulator (because small rainfall simulator tests were finished before the large simulator tests were contemplated and the topography of the small rainfall simulator area was not suitable for the large simulator) but the soil type was the same, slopes were similar, and the pasture and grazing regime were the same. The flow was guided to a flume by means of a 10-m-long wing wall. Samples of the outflow from the rainfall simulator were collected manually at intervals throughout the runoff period and taken without delay to a laboratory for analysis of suspended solids and nutrients. Event-mean concentrations (load divided by runoff volume) were calculated for each event from the measured concentrations in conjunction with the flows at the times of sampling. The concentrations in these experiments were usually higher during the first part of the rising limb of the hydrograph and lower during the falling limb. However, the concentrations during the first and last part of the hydrograph made relatively minor contributions to the load of sediment and volume of runoff because the flow was low. Hence, it is appropriate to use the event-mean concentration as a representative concentration when discussing contaminant losses.

The amount of bare ground was measured at 2-m spacings along 2 transects by observing the number of points with bare ground under the cross-points of a grid of fine wires (200 points in the grid, 45-mm spacing). The soil moisture was measured at 6 locations using Campbell Scientific CS615 moisture probes inserted 250 mm into the soil surface (measuring average soil moisture over that depth), with adjacent temperature probes for a temperature correction to the moisture rating curve.

#### Chemical analysis

Suspended solids (SS) concentrations were determined by weighing after filtration on a glass fibre filter and drying at 104°C (method 2540D, APHA 1995). Dissolved nutrients were determined after filtering with a 0.45- $\mu\text{m}$  membrane filter. Ammonium nitrogen ( $\text{NH}_4\text{-N}$ ) was determined by indophenol blue colourimetry via flow injection analysis on a Lachat Instruments autoanalyser (NWASCO 1982). Nitrate plus nitrite nitrogen ( $\text{NO}_3\text{-N}$ ) was determined by cadmium reduction followed by sulfanilamide/NEDD diazotisation on a Lachat FIA autoanalyser (Lachat Instruments QuickChem method 31-107-01-1-A). Dissolved reactive phosphorus (DRP) was determined by molybdenum blue colourimetry via a Lachat FIA autoanalyser (Lachat Instruments QuickChem method 31-115-01-1-I). Total dissolved nitrogen (TDN) and total nitrogen (TN) were determined by alkaline persulfate digestion (Grasshoff *et al.* 1983) and colourimetry (as above for nitrate). Total Kjeldahl nitrogen (TKN) was determined by acid digestion followed by indophenol blue colourimetry. Total dissolved phosphorus (TDP) and total phosphorus (TP) were determined by acid persulfate digestion (NWASCO 1982) with colourimetry (as for DRP). Dissolved organic phosphorus (DOP) was calculated from TDP minus DRP. Dissolved organic nitrogen (DON) was calculated from TDN minus  $\text{NO}_3\text{-N}$  minus  $\text{NH}_4\text{-N}$ . Particulate phosphorus (PP) was calculated from TP minus TDP. Particulate nitrogen (PN) was calculated from TN minus TDN.

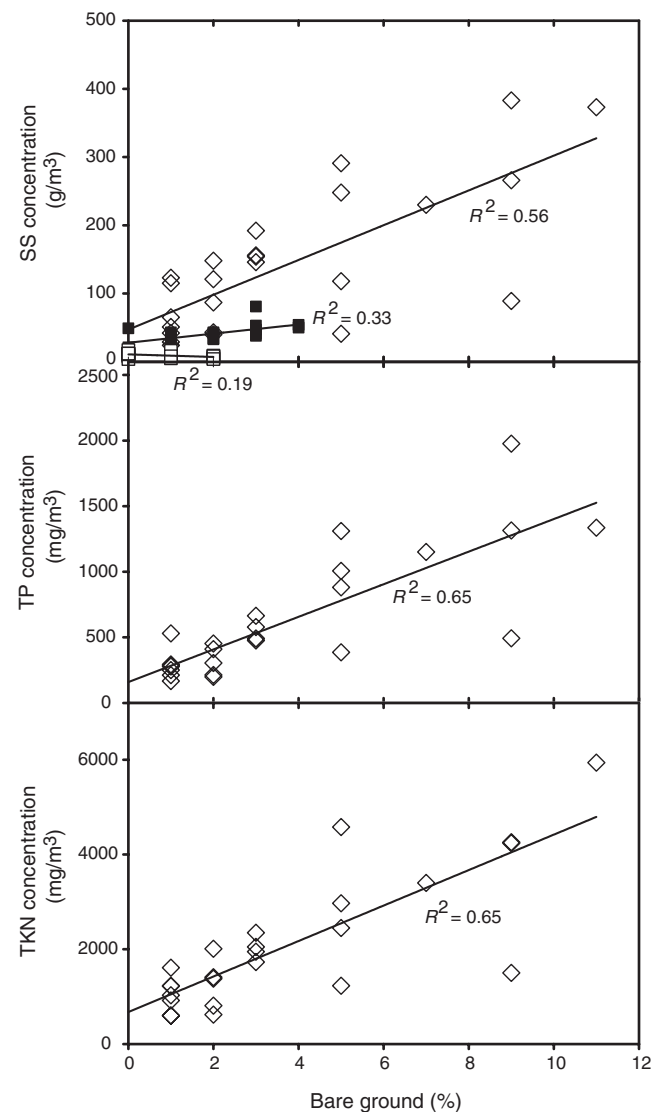
## Results and Discussion

### Effect of grazing on concentrations of contaminants

The experiments with the small rainfall simulator show that the concentrations of SS, TP, and TKN after grazing increase linearly with the amount of bare ground (Fig. 1). No other chemical parameters were measured with the small rainfall

simulator tests. A similar trend was found in cattle-treading experiments (Elliott *et al.* 2002). As the amount of bare ground was greatest after grazing, we conclude that sheep grazing increased the concentrations.

There were non-zero concentrations for zero bare ground. For example, the intercept for the line for SS for July in Fig. 1 was 47  $\text{g}/\text{m}^3$  ( $P = 0.05$ ), which corresponds to the increase in concentration that would occur with an increase in bare ground of 2%. The non-zero intercept is consistent with the findings from cattle-treading experiments (Elliott *et al.* 2002), and could be due to some component of shear entrainment even for the small plots.



**Fig. 1.** Concentration of suspended solids (SS), total phosphorus (TP), and total Kjeldahl nitrogen (TKN) v. bare ground and time since treading for the small rainfall simulator experiments. The dates are 30 July ( $\diamond$ ), immediately after grazing), 10 September ( $\blacksquare$ ), 6 weeks after grazing), and 25 November ( $\square$ ), 3 months after grazing). The lines are linear fits to the data.

**Table 1. Description of the large rainfall simulator experiments and runoff results**  
The runoff coefficient is the volume of runoff divided by the volume of applied rainfall

Run	Description	Date	Conditions	Antecedent moisture (%)	Application rate (mm/h)	Runoff coefficient
A	Summer pre-graze	16 January	No grazing for 8 weeks	50.1	35.5	0.39
B	Summer post-graze	25 January	Grazed for 8 days, 230 ewes/ha	48.2	35.6	0.41
C	Winter pre-graze	31 May	No grazing for 7 weeks	47.5	35.5	0.37
D	Winter post-graze	7 June	Grazed for 4 days, 750 ewes/ha	45.1	34.7	0.21
E	Winter 2 weeks post-graze	23 June	2 weeks since heavy grazing. Extra damage to pasture immediately after Run D	48.8	30.7	0.54

**Table 2. Concentrations from the outlet of the rainfall simulator area**  
SS, Suspended solids; DRP, dissolved reactive P; DOP, DON, dissolved organic P, N; PP, PN, particulate P, N; TP, TN, total P, N

Run	Description	Bare ground (%)	SS (g/m <sup>3</sup> )	DRP	DOP	PP	TP	NH <sub>4</sub> -N	NO <sub>3</sub> -N <sup>B</sup> (mg/m <sup>3</sup> )	DON	PN	TN
A	Summer pre-graze	0.2	13.4	16.8	25.7	44.0	86.5	35.5	341 (660)	533	276	1180
B	Summer post-graze	5.4	40.4	271	85.1	172	529	604	533 (458)	1130	879	3150
C	Winter pre-graze	0.1	30.5	20.6	27.7	76.2	124	65.5	306 (493)	447	360	1180
D	Winter post-graze	16.8	394	1570	193	879	2640	2170	614 (822)	2210	5660	10700
E	Winter 2 weeks post-graze	14.8 <sup>A</sup>	584	67.3	34.4	538	639	157	945 (1060)	441	3040	4580
Tank supply				3–13	7–17	4–29	26–55	4–13	458–1060	89–146	21–56	608–1240

<sup>A</sup>The bare ground was 39% in an area 10 by 10 m near the outlet weir.

<sup>B</sup>Tank supply NO<sub>3</sub>-N concentrations for each run are in parentheses.

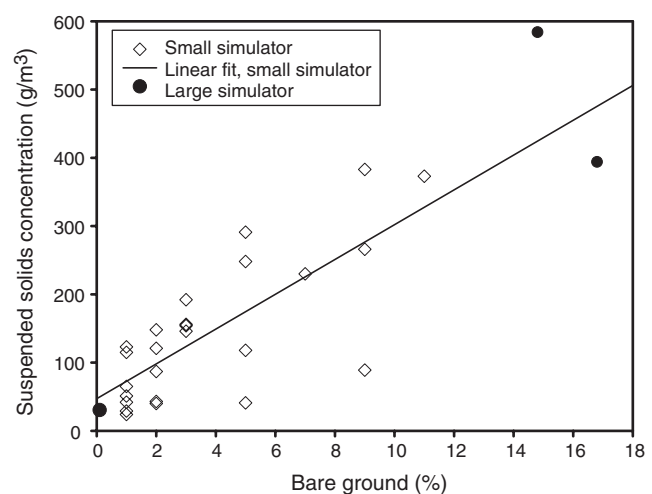
The runs with the large rainfall simulator also showed higher concentrations after grazing (Tables 1 and 2). Summer grazing increased the concentrations of SS, PN, and PP by a factor of 3, and winter grazing increased concentrations of the same parameters by a factor of 13–16. The greater effect in winter is related in part to the greater increase in bare ground in winter (associated with the more intense grazing and more palatable grass).

The concentrations of DRP and NH<sub>4</sub>-N increased markedly after grazing, with a particularly dramatic increase in winter (by a factor of 33 for NH<sub>4</sub>-N and 76 for DRP). This is presumably associated with the wash-off of dung and urine following grazing (consistent with the green smelly nature of the samples after grazing in winter). The paddocks were unfertilised, so the high concentrations were not associated with fertiliser use.

The increases in concentrations of DOP and DON were not as marked as the increases in DRP and NH<sub>4</sub>-N, and were comparable to the increases in particulate nutrients and SS. This is contrary to our expectation that the dissolved organic nutrients after grazing would be dominated by contributions from animal wastes and hence would increase to the same degree as DRP and NH<sub>4</sub>-N.

We cannot distinguish whether the concentration of NO<sub>3</sub>-N increased after grazing, because the concentration in the feed water was variable and comparable to that in the runoff.

The concentrations of SS for the post-grazing winter experiments with the large rainfall simulator were comparable to those from the small rainfall simulator after



**Fig. 2.** Comparison between suspended solids concentrations for the large and small simulators after grazing. The line is a regression to the small simulator data.

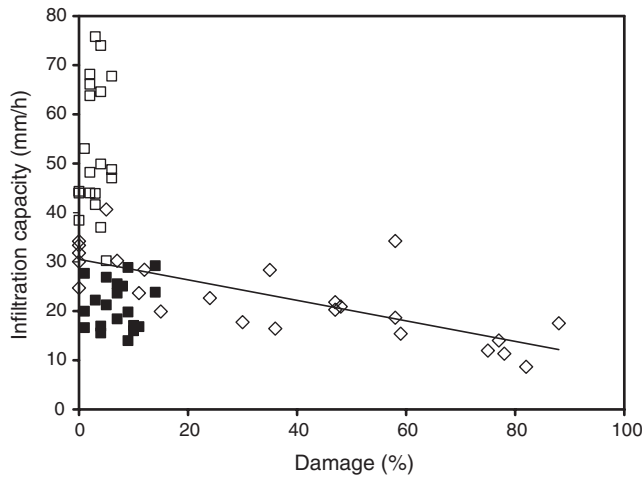
grazing (Fig. 2). This could just be fortuitous, as there are differences in rainfall rate, energy per unit rain depth, spatial scale, and time of year that have not been accounted for in a consistent fashion. The TP and TKN concentrations were also comparable for the 2 types of rainfall simulator.

#### *Effect of grazing on infiltration capacity*

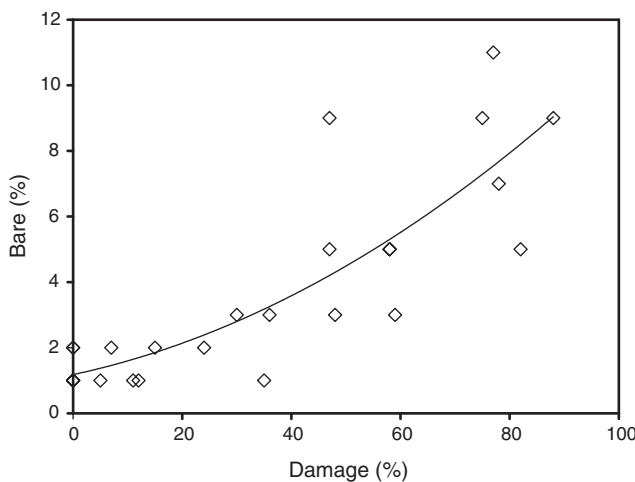
In the small rainfall simulator experiments there was an inverse relationship between grazing-induced damage to the ground and infiltration capacity in July (immediately after

grazing) (Fig. 3,  $R^2 = 0.57$ ,  $P = 0.0008$  for the slope term). This indicates that grazing modifies the soil properties (for example, by smearing the soil surface and closing off macropores) and hence reduces the infiltration capacity, as found in similar experiments with cattle (Nguyen *et al.* 1998). There was also an inverse (but weaker) relation between the infiltration capacity and the amount of bare ground immediately after treading, which is not surprising as the amount of damage is related to the amount of bare ground (Fig. 4).

In the large rainfall simulator experiments in summer, grazing did not affect the amount of runoff (see the runoff coefficients in Table 1). From casual observations, the soil was relatively firm so that there was little likelihood of damage to the soil as a result of grazing. We expected winter



**Fig. 3.** Steady-state infiltration rate *v.* damage and time since treading for the small rainfall simulator experiments. The dates are 30 July ( $\diamond$ , immediately after grazing), 10 September ( $\blacksquare$ , 6 weeks after grazing), and 25 November ( $\square$ , 3 months after grazing).



**Fig. 4.** Relation between bare ground and ground damage immediately after treading in winter. The line is a quadratic fit to the data.

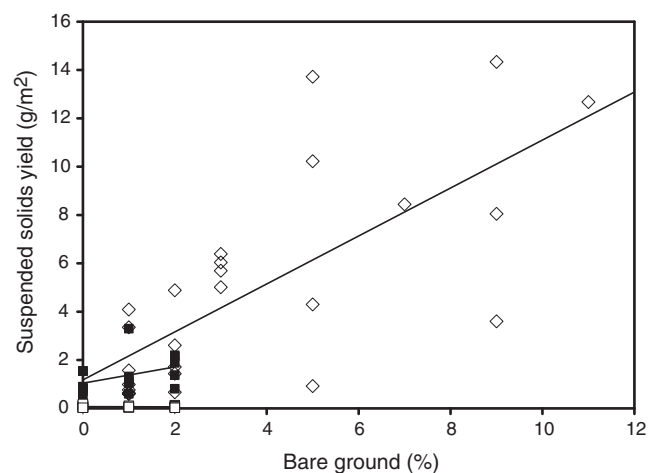
grazing to increase the runoff coefficient (that is, decrease the infiltration capacity), but this was not demonstrated clearly by the large rainfall simulator tests due to experimental difficulties. In Run D (immediately after grazing) the wind blew some rain off the weir catchment. In Run E (2 weeks after grazing) the runoff increased, but there was  $\sim 150$  mm of rain over the preceding 2 weeks, over which time the soils around the farm seemed to become very wet and boggy (although this is not reflected strongly in the antecedent soil moisture values).

*Effect on load*

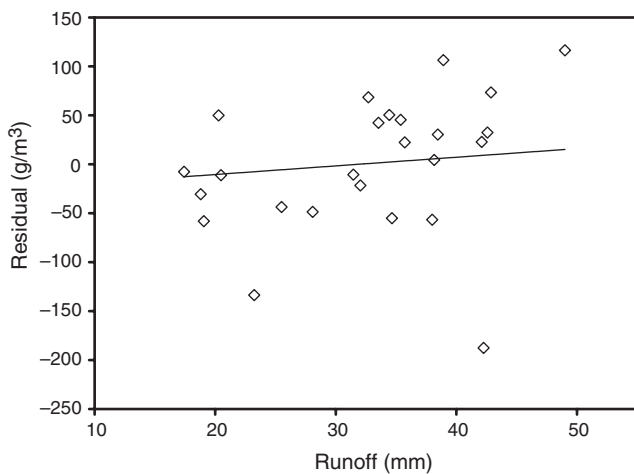
In the small rainfall simulator experiments, grazing increased the concentration of sediment in runoff and increased the amount of runoff produced. The net result was to increase the load of sediment (Fig. 5). As the load is concentration  $\times$  runoff, and both of these vary with the amount of bare ground, we might have expected a non-linear relation between bare ground and load per event. This is not evident in the winter results, probably due to the small grazing-associated variations in runoff ( $\pm 7$  mm compared with typical runoff of 33 mm) and data scatter. The combined effect of runoff and concentration would probably be more prominent for smaller rainfall events.

*Seasonal effects on erodibility and infiltration capacity*

In the small rainfall simulator experiments, the infiltration rate was higher in summer than in winter; the mean infiltration capacity was higher in November (51.2 mm/h) than in July (28.6 mm/h) for plots with  $<20\%$  initial damage ( $P = 0.02$  for 1-sided paired *t*-test). The infiltration capacity in September (23.6 mm/h) was a little less than that in July ( $P = 0.06$ ). This agrees with results from a study of cattle treading (Elliott *et al.* 2002).



**Fig. 5.** Yield of suspended solids for 30 July ( $\diamond$ , immediately after grazing), 10 September ( $\blacksquare$ , 6 weeks after grazing), and 25 November ( $\square$ , 3 months after grazing). The lines are linear fits to the data.



**Fig. 6.** Regression residuals from a linear regression of concentration *v.* bare ground, plotted against runoff for the winter experiments with the small rainfall simulator. The line is a linear fit to these residuals (slope =  $0.88 \text{ mg/m}^3 \cdot \text{mm}$ ,  $P = 0.02$  for the slope term).

In the small rainfall simulator experiments, the concentration of suspended sediment for a given amount of bare ground decreased with time (Fig. 1). Also, for plots with low amounts of grazing (<2% initial bare ground), suspended sediment concentrations decreased from July to September (paired *t*-test 1-sided  $P = 0.05$ ) and from July to November ( $P = 0.002$ ). We suspect these results can be attributed mainly to a seasonal variation in soil erodibility (where erodibility is considered here as a mass of material detached by rain impact per unit energy of rain). However, the lower concentrations in summer could also be partly associated with the lower runoff rate, as the concentration tended to increase slightly with runoff for any given time in the year (Fig. 6), which is consistent with the results from earlier studies (Elliott *et al.* 2002).

In the large rainfall simulator pre-grazing experiments, the concentrations of suspended solids were higher in winter than in summer, despite there being comparable vegetative cover and runoff volumes, which supports the idea of a seasonal variation in erodibility. Also, in the large rainfall simulator post-grazing experiments, the concentration per unit bare ground was higher in winter than in summer. These results suggest that soil erodibility is higher in winter (by a factor of 2–3), which is consistent with the results from the small rainfall simulator and earlier studies (Elliott *et al.* 2002).

Such seasonal variations are important, as they compound the effects of grazing. In winter there is higher rainfall, less permeable soil, higher erodibility, and greater likelihood of high pasture removal (due to restricted feed), which combine to give a much greater risk of sediment and nutrient loss in winter than in summer. The practical implications are that management of feed reserves, vigilant stock management to avoid over-grazing, and management of stock numbers are of

particular importance in winter for avoiding grazing-related contaminant loss.

The seasonal variations measured at this site will not apply universally. Blennerhassett (1998) measured higher concentrations of DRP in summer for a dry East Coast area where hydrophobic soils increase the likelihood of overland flow in summer. McColl and Gibson (1979*b*) measured the greatest effect of treading in summer and autumn, which was attributed to faecal matter and urine remaining on the surface for longer when the soil was dry. Also, in drought-prone areas there is a higher risk of bare ground in summer.

#### *Recovery after grazing*

In the small rainfall simulator experiments 6 weeks after grazing there were no significant correlations for the following pairs of variables: the amount of bare ground and the initial amount of bare ground (i.e. the amount of bare ground just after grazing) ( $P = 0.24$ ); the damage and the initial damage ( $P = 0.59$ ); the sediment concentration and the initial bare ground ( $P = 0.96$ ); and the infiltration capacity and the initial damage ( $P = 0.25$ ). We conclude that the ground recovered from the effects of sheep grazing within 6 weeks, both in terms of concentrations of contaminants and infiltration rates. This agrees with the findings of McColl and Gibson (1979*c*). These recovery times are faster than the value of >2 months for similar experiments with cattle treading (Elliott *et al.* 2002). Presumably the heavier cattle result in deeper and more severe damage to the ground, which takes longer to repair.

In the large rainfall simulator tests in winter, the concentrations of DRP and  $\text{NH}_4\text{-N}$ , decreased markedly in the weeks after grazing (by a factor of 14–23). The concentrations of PN and PP did not decrease so markedly, and the concentration of sediment increased, which can be attributed to extra ground damage caused by trampling near the outlet weir immediately after the first rainfall simulation, and persistent wet weather with little pasture re-growth. McColl and Gibson (1979*b*) found that nitrate concentrations rose in the weeks after grazing, but we could not observe such changes due to the nitrate in the tank supply water also rising over this period.

#### *Comparison with catchment-scale data*

The highest event-mean sediment concentration measured in these experiments was approximately  $600 \text{ g/m}^3$ . At any given time only part of the catchment will be in a freshly grazed state, and the grazing would not be as intense as in the experiments, so the concentration averaged over a farm would be expected to be considerably < $600 \text{ g/m}^3$ . The maximum concentration measured at the outlet of a 2.6- $\text{km}^2$  catchment over a 2-year period (1996–97) on the same farm (Quinn and Stroud 2002) was  $722 \text{ g/m}^3$ , suggesting that sources of sediment other than overland flow are important at the catchment scale. More strikingly, a concentration of

49 200 g/m<sup>3</sup> was measured during a 20-year return-period storm in 1998 when stream-bank erosion and many slips occurred, and this concentration is much greater than would be expected in overland flow (based on the rainfall simulator experiments).

A coarse estimate of SS yield can be obtained from the rainfall simulator results. A typical concentration in winter after moderate grazing would be 200 g/m<sup>3</sup>. Allowing for a linear decrease to 'background' concentrations of 30 g/m<sup>3</sup> over 3 weeks and a grazing cycle of 8 weeks, the cycle-averaged concentration is approximately 60 g/m<sup>3</sup> in winter. In summer the comparable concentration is 20 g/m<sup>3</sup>. Allowing for 30 mm of overland flow per year in winter–spring and 10 mm in summer–autumn (as indicated in monitoring of natural overland flow over a 2-year period in the study area; data not presented), the annual yield of sediment would be 20 kg/ha.year. This is much lower than the yield of 2100 kg/ha.year measured at the catchment scale, which is most likely due to mass erosion processes (Quinn and Stroud 2002). Similar calculations for TP give a yield of approximately 0.1 kg/ha.year, which is lower than the catchment yield of 2.4 kg/ha.year. For nitrogen the inferred yield in overland flow is 0.8 kg/ha.year compared with the catchment yield of 16 kg/ha.year. Despite the very coarse nature of these calculations, it is clear that the loss of sediment and nutrients in overland flow is small in relation to the export at the catchment scale. This suggests that management of grazing to reduce sediment and nutrient loss in overland flow could have a relatively minor effect on the export of nutrients at the larger catchment scale.

### Conclusions

Grazing by sheep on hill-country pasture increased the concentrations of SS and nutrients in overland flow, both for summer and winter grazing. In the most extreme case (large rainfall simulator in winter), grazing increased the concentrations by a factor of 33–76 for DRP and NH<sub>4</sub>-N; 13–16 for SS, PP, and PN; and 5–7 for DOP and DON.

The concentrations of sediment and particulate nutrients increased with the amount of bare ground as has been demonstrated previously in relation to cattle treading (Elliott *et al.* 2002). Some sediment and nutrient is washed off pasture with complete grass cover (0% bare ground).

The small rainfall simulator experiments showed that intensive grazing reduces the infiltration capacity by up to 66%, although this effect was not established clearly with the large rainfall simulator experiments.

The data on bare ground, soil damage, infiltration rate, and concentration of sediment and nutrients all showed no effect of grazing after 6 weeks. In the large rainfall simulator experiments, the concentrations of DRP and NH<sub>4</sub>-N dropped sharply in the 2 weeks after grazing.

The soil erodibility varied seasonally, with the concentrations of SS in winter experiments about 2.5 times

the concentration in summer for the same amount of bare ground. The small rainfall simulator experiments also showed a seasonal variation in infiltration capacity, with the summer infiltration capacity approximately double the winter value. This is of practical significance, because in winter, higher rates of runoff generation (low infiltration rates) will coincide with a higher likelihood of pasture removal (due restricted feed supply), higher treading damage (softer ground), and higher soil erodibility. These factors are likely to lead to high contaminant loads in winter, so pasture and grazing management are particularly important in winter at this site.

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