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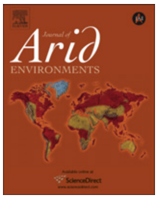

Effects of cattle trampling on vegetation, infiltration, and erosion in a tropical rangeland☆,☆☆

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A B S T R A C T

Cattle trampling without forage consumption at stocking densities of 0.03–1.4 cows ha^{-1} was simulated on two dry-season rangelands in Kenya. Experiments under artificial rainfall documented the response of plant cover and production, infiltration, and erosion on a Luvisol and a Vertisol. Trampling reduced plant cover, biomass, and, at the highest rate, regeneration in the ensuing wet season. Infiltration was reduced on the Vertisol but not the Luvisol, although increases in runoff due to trampling were slight. Trampling increased soil loss partly by reducing vegetation cover but mainly by disrupting surface layers of sand on the Luvisol and of clay aggregates on the Vertisol. Soil loss normalized by runoff and rainfall energy declined in a sequence of erosive rainstorms as the sandy surface layer became re-established, but before vegetation recovered. Establishment of a sandy armor layer during runoff events and its disruption by dry-season trampling thus strongly affect soil-loss rates. Trampling limits plant recovery in the ensuing wet season only at intensities typical of settlement and watering centers. The experimental results, generalized with a spatial model of stock density, can be used to estimate the contribution of trampling to forage production and erosion as herding patterns change in response to sedenterization and water development.

1. Introduction

Trampling by livestock has major, predominantly deleterious effects on subhumid rangelands where studies have been conducted on the effects of simulated animal stocking on plant cover, infiltration, runoff, and soil loss. Trampling may either compact or disturb and loosen the soil surface, rendering it more susceptible to runoff and erosion. Indirect effects result when trampling damages plants, reduces vegetation cover and infiltration, and increases runoff. Damage to plants may also result in short- or long-term reductions in biomass and primary production. Schlesinger et al. (1990) have emphasized the deleterious effects of concentrated use of arid lands by cattle and off-road vehicles.

The high stocking rates and intense rainfall of tropical subsistence rangelands tend to accelerate erosion well above long-term geological rates even on gentle slopes (e.g. Dunne et al., 1978), but the various components of grazing effects are not well understood (Warren et al., 1986). Although it is possible to incorporate the effects of cover reduction through forage consumption into models of runoff and soil loss, the mechanical effects of trampling are not quantified and therefore it is difficult to incorporate trampling into models of how stocking density affects hydrology and erosion. Separation of trampling and forage consumption effects becomes important, for example, if one is comparing two stocking systems in which the distances traveled for water are radically different. In many subsistence pastoral ecosystems the distances traveled are larger than on more capital-intensive ranches, stock concentrations around water sources and settlements are often greater, and thus one might expect the soil disturbance per unit of stock density or forage consumption to be larger. Other interest in the role of trampling has arisen in discussions of the intensive rotation grazing method of range management (Savory and Parsons, 1980) whereby large numbers of livestock are concentrated on small areas under the assumption that intensive trampling of the soil surface will

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enhance infiltration and reduce erosion, even when conventional stocking rates are doubled or tripled (Warren et al., 1986).

We present the results of a set of experiments designed to quantify the effects of dry-season trampling by cattle in the absence of grazing on plant cover and production, infiltration and soil loss. The results also illuminate the processes of runoff, erosion, and biotic response that affect soil loss in a dry-season range. We simulated trampling at various stocking densities on a sandy clay Luvisol and a clay Vertisol in southern Kenya, and measured the resulting changes in plant cover, biomass, infiltration capacity, and soil loss on plots under artificial rainfall. Then we irrigated the plots on the Luvisol with a series of erosive and non-erosive rainstorms over a 35-day period to simulate a wet season. Runoff and soil loss were measured, and the ground cover and plant biomass and production were monitored at intervals during the period. On the Vertisol we measured changes in plant cover caused by the trampling, and then subjected each plot to two erosive rainstorms on the same day. We did not measure plant recovery after experiments on the Vertisol.

Our purposes in the experiments were as follows:

(1) To relate stocking density (cow-years ha^{-1}) to the intensity of trampling (the density of hoofprints m^{-2}) by considering distances and spatial patterns of animal travel;
(2) To measure the effect of trampling intensity on plant cover, both immediately and during the wet-season recovery, but not over a longer period of alternating dry-season trampling and wet-season growth;
(3) To quantify whether and how trampling affects infiltration and soil loss;
(4) To provide insight into the mechanisms by which trampling affects plant cover and production, infiltration, and soil loss;
(5) To parameterize a model of how results from experiments on trampling can be scaled up from plots in order to estimate landscape-scale effects of trampling on plant cover and soil erodibility.

2. Previous studies of the effects of trampling on rangelands

Abdel-Magid et al. (1987b) and Gifford and Hawkins (1978) reviewed their own and other field studies concerning grazing effects on infiltration and runoff in North American grazing lands, but they found the results to be extremely variable and insufficient for separating the effects of trampling from those of forage consumption. Trampling appears to have influenced various studies of erosion in rangelands, but without being quantified. In the Middleveld of Swaziland, measurements of soil loss on 1 m^2 plots under artificial rainfall were not significantly correlated with vegetation cover because an important complicating factor was “the amount of loose material on the soil surface awaiting removal at the start of each storm. This will depend on the level of initial disturbance caused by cattle grazing on the land” (Morgan et al., 1997, pp. 296–297). The description of grazing pressure in the study area suggests that trampling is the cause of the disturbance. In studies of erosion on 1 m^2 plots in Australian paddocks stocked at two densities with sheep and kangaroos stocking rate did not affect soil compaction or infiltration, but on bare soil the soil-loss rate in the heavily stocked paddock was 36% higher than on the lightly stocked paddock, a result that Greene et al. (1994) ascribed to greater hoof activity in pulverizing the upper 2 cm of soil.

There is little information on the effects of trampling on plant cover, infiltration, runoff, and soil loss in tropical rangelands under subsistence grazing, which is highly seasonal and particularly intense around water sources and migration pathways. For example, Tongway et al. (2003) measured changes in species composition with radial distance from watering points in an Australian rangeland and concluded from their systematic surveys of soil-surface condition that despite strong patchiness in land surface condition, “Increasing erosion closer to water was a key degrading process” (Tongway et al., 2003, p. 301). They used distance to water as an index of stock use intensity.

Most experimental studies of the effects of cattle trampling on vegetation and hydrological properties have been conducted with metal plates and artificial hooves on boxes and plots of soil under laboratory conditions (Abdel-Magid et al., 1987a; Dadkah and Gifford, 1980; Packer, 1953; Sun and Liddle, 1993), or with a cow on a tilled and rolled surface with artificial plant-like canopies (Savabi and Gifford, 1989). The plots were subjected to a standard artificial rainstorm, and comparisons were made of the total amount of soil lost from each plot. Warren et al. (1986) studied runoff and erosion effects due to cattle trampling at various controlled stocking rates on a clay soil, similar to one of our own sites, but which had not been grazed for 7 years and had its cover of forbs removed with herbicide. They quantified the effects of stocking density and initial moisture content on infiltration rates and soil loss from bare 0.5 m^2 plots with a sprinkling infiltrometer.

The closest analogue to the current field study is that of Fierer and Gabet (2002), who used essentially the same methodology and equipment on steep hillsides near Santa Barbara, CA to measure the influence of trampling on carbon and nitrogen losses in runoff. Trampling strongly decreased the infiltration capacity of a 1–2 cm thick biotic crust on the smectitic soil, increasing runoff and nutrient loss. Only the study by Warren et al. (1986) among the above-mentioned reports defined a relationship to stocking density, and none quantified any connection to landscape-scale patterns of trampling intensity.

3. Study area

The experiments were conducted in two areas of Kajiado District, southern Kenya: Eremito Ridge in the Amboseli lowland (150 km SSE of Nairobi at the northern boundary of Amboseli National Park) and the Athi-Kapiti Plains (25 km south of Nairobi, adjacent to Nairobi National Park). During the two dry seasons of each year, these rangelands were heavily stocked by migrant herds of wild herbivores and by the cattle and small stock of Maasai pastoralists. Herds dispersed from these rangelands during the wet seasons (Western, 1973, 1975). The geology, topography, and soils of the experimental sites have been described in detail elsewhere (Dunne and Dietrich, 1980a).

The hillslope studied at Amboseli, which had been used for other studies of hydrology, erosion, and Maasai settlement patterns (Dunne and Aubry, 1986; Dunne and Dietrich, 1980a,b; Dunne et al., 1978, 1991; Western and Dunne, 1979), was underlain by a reddish brown, kaolinitic, sandy clay Luvisol (FAO, 1998) with an organic content of less than 1% and a bulk density of 1.3–1.6 g cm^{-3} in cores taken from the upper 10 cm. It had a subtle platy structure in the upper 2 cm, and a 2–5 mm-thick sandy layer at its surface. Below the 2 cm depth, the soil was structureless. The gradient of the site was 0.02, typical of the area. The soil studied on the Athi-Kapiti Plains was a clay Vertisol (FAO, 1998) with cracks up to 2 cm wide and 80 cm deep spaced at intervals of ~50 cm during the dry season. The organic content of the upper 10 cm was 9%, and the surface was covered with a ~5 mm-thick layer of pebble- and sand-size aggregates of clay. Below this layer the dry soil had an angular, blocky structure with a bulk density of 1.05–1.1 g cm^{-3} in the upper 10 cm. The gradient of the experimental site was 0.025. At neither site did we observe biogenic crusts of the kind described

Table 1
Trampling intensities and equivalent stocking densities (cow-equivalents per ha referred to as cows ha^{-1} for brevity) for the plots used in the study.

Region	Trampling condition	Plot No.	Artificial trampling (hoofprints m^{-2})	Total trampling (hoofprints m^{-2})	Simulated stocking rate including background rate (cows ha^{-1})
Amboseli	Livestock-free	11	0	16	0.03
	Background	10	0	97	0.125
	Background	9	0	97	0.125
	Near-background	6	10	107	0.14
	Medium intensification	7	100	197	0.25
	Strong intensification	8	1000	1097	1.41
Athi-Kapiti	Background	18	0	377	0.286
	Near-background	15	10	387	0.29
	Medium intensification	16	100	477	0.36
	Strong intensification	17	1000	1377	1.04

from less disturbed sites (Belknap, 1995; Eldridge, 1998; Johansen, 1993; Schmidt and Karnieli, 2000).

Mean annual rainfall at the time of the experiments was approximately 250 mm at Amboseli and 750 mm on the Athi-Kapiti Plains (Government of Kenya, 1970) with large inter-annual variations. The rains are concentrated in two seasons of 30–60 days duration, separated by long dry seasons. The plant cover at both sites was bushed grassland (Pratt et al., 1966) dominated by *Balanites glabra*, *Acacia mellifera* and *Acacia nubica* in the woody stratum and *Sporobolus homblei*, *Chloris rocksburghiana*, *Cenchus ciliaris* and *Eragrotis keniensis* grasses among scattered *Serciocompsis pallid*, a dominant low shrub of the herb layer (Western, 2006).

On the Amboseli plots the plants had been grazed down to their basal cover, which averaged 10% (9–12%), near the end of the dry season, while a plot in a nearby livestock-free portion of Amboseli on similar soil had a basal plant cover of 16%. The Athi-Kapiti plots had an average plant cover of 72% (69–74%) at the time of the experiments and a basal cover averaging 36%, measured after clipping of all stems. Both study areas had suffered a severe 4-year drought when our study was conducted, and grass stems were reduced to ~2 cm. Livestock numbers had fallen to half their pre-drought levels due to starvation. The prevailing range condition was therefore heavily degraded, and the stress on the plants from trampling, grazing, and water deprivation was unusually great.

4. Methodology

We installed four adjacent plots at Amboseli (plots 6–9 in Table 1) and Athi-Kapiti (plots 15–18) for studies of the effects of trampling on plant cover and biomass, infiltration rate, and erosion. Each plot was 5 m long and 2 m wide, and was bounded by a metal strip and fitted with a runoff collector, as described by Dunne and Dietrich (1980a). A rainfall simulator described by Dunne et al. (1980), which produced raindrops of natural size and impact velocities was set up over each plot for studies of infiltration and erosion.

On each plot we simulated the trampling to be expected under a specified density of stocking with cattle. On plots 6–8, we simulated trampling under three stocking densities above the background rate of 0.125 cow-equivalent years ha^{-1} (henceforth referred to as cows ha^{-1} for brevity), leaving plot 9 at the background rate (Table 1). The relation of the simulated trampling intensities to those found in the grazed landscapes is described in the following section. Simulation was necessary because of the difficulty of using cattle to trample the small experimental plots. Trampling was done by a 75 kg man, who wore shoes made from the hind pair of a cow's hooves (Fig. 1). The mean body weight of zebu cattle in the region is 180 kg when averaged over all age classes in the population (Watson, 1969). Thus, the average static pressure exerted by the hooves beneath our bipedal subject was 83% of that beneath an average quadruped zebu cow.

The average stocking density and duration of trampling for each area are known from long-term census records (Western, 1975), and include the effect of wildlife, mainly zebra and wildebeest, which constitute 20% of the total live weight, as well as cattle, sheep and goats. Cumming and Cumming (2003) demonstrated, using the average adult female as an index, that hoof pressures are nearly identical among all standing ungulates, regardless of their body size. Ssemakula (1983) showed that hoof pressures of sheep and goats were 70–75% of those of cattle on a commercial ranch in southern Kenya, but the cattle were heavier than those of traditional pastoralists in our study area. Cumming and Cumming (2003) calculated that, since travel distances scale with body mass, the equivalent biomass of cattle would exert close to twice the total trampling force per day of an indigenous herbivore community in Zimbabwe, although the trampling force from sheep and goats would be only 40–60% of that imposed by cattle in the same community. On the other hand, Pennycuick (1975) showed

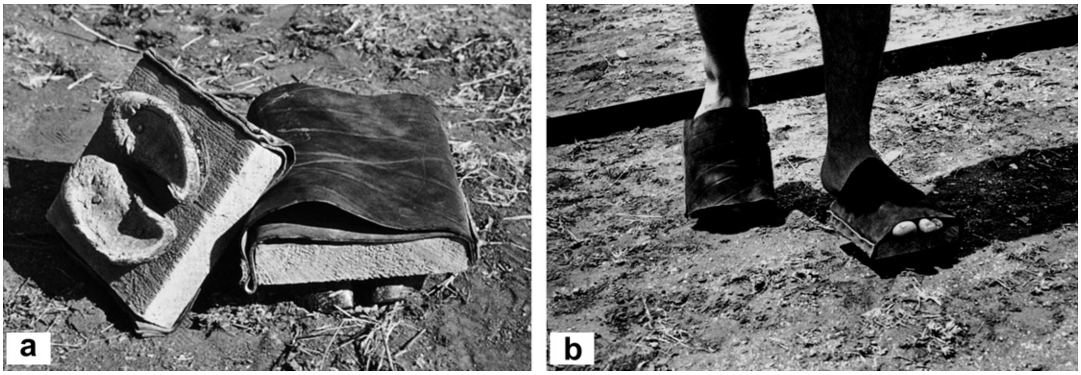

Fig. 1. (a) Shoes made from cow hooves used to simulate the effects of trampling by livestock; (b) use of the shoes in trampling a plot.

that the number of an ungulate's feet touching the ground simultaneously decreases with increasing gait speed from approximately 3 to 2 as the animal accelerates from a very slow walk to 3.6 km h^{-1}. In the face of these sources of variation, we expressed the biomass of all large herbivores in terms of the dominant animal, namely as cow-equivalents in terms of weight (Table 1).

Our own close observations of the effects of trampling on the dry soil indicated that the shearing action of hooves in disrupting the surface was more influential than the normal pressure in consolidating it. Thus, our bipedal subject practiced a walking gait that resulted in simulated hoofprints that Maasai herdsmen could not differentiate from the tracks of cattle adjacent to the plots. The hoofprints had the correct degree of indentation, and the shoes sheared the soil and flicked it backwards in the late stages of each step to create a small rampart of soil at the back of each print. Differences in the condition of the plot surface between the original condition and the heaviest trampling effect are shown in Fig. 2.

Before and after the trampling treatments, we measured the plant cover and the standing crop of vegetation, which in Amboseli had already been grazed down to its basal cover of approximately 10% by the time of our experiments, conducted after several years of drought. Ground cover was measured with the pin-intercept method (Greig-Smith, 1957), and the standing biomass (M, g cm^{-2}) was derived from the product of height and cover measurements using an equation developed in Amboseli by Western and Lindsay (1984)

$$\log M = 1.02\log(HC) - 0.38 \left(r^2 = 0.89; n = 42\right) \quad (1)$$

where H is mean plant height (cm) and C is cover expressed as a percentage. The equation also predicts the biomass of the Athi-Kapiti grasslands (Gichohi, 1990).

After trampling, each Amboseli plot was subjected to a 1-h-long artificial rainstorm on dry antecedent conditions. The spray nozzle used generated an average intensity of 72 mm h^{-1}, a median drop size of 2.0 mm, and a kinetic energy of 18 J m^{-2} mm^{-1} (Dunne et al., 1980). Runoff rate and soil-loss rate were measured at intervals of one to several minutes during the experiments by timing the collection of 1-l water samples draining from a trough cemented into the ground at the lower end of each plot. The infiltration rate was calculated by subtracting runoff rate from rainfall intensity after runoff had stabilized. Our measurements of rainfall at intervals of 15, 20 or 30 min during the experiments allowed us to define fluctuations of rainfall intensity due to variations in the operation of the pumping system. When the changes in rainfall intensity were sustained for long enough, runoff again attained steady state and a new value of infiltration rate could be computed, producing two values during some experiments. We also measured infiltration rate on two other plots on the same soil. Plot 10 was situated on the same hillside with the same gradient and was essentially identical to Plot 9, which received no artificial trampling. Plot 11, with a slightly sandier soil and a gradient of 0.05, was so distant from a water supply that it was grazed and trampled only by wildlife at an annual stocking density of 0.03 cow-equivalents ha^{-1}.

The mass of soil lost during each experiment was measured by filtering and weighing sediment from the timed samples and integrating the soil-loss rate over the duration of runoff. Soil loss was then expressed in g m^{-2} mm^{-1} of runoff and per J m^{-2} of rainfall energy (hereafter referred to as normalized soil loss in g mm^{-1} J^{-1}) to minimize the effects of differences in runoff volume and rainfall kinetic energy between experiments.

The plots were then fenced off from grazing animals for 35 days, and the plots were watered five times with a non-erosive fine spray to simulate a wet season, during which the ground cover and standing crop were measured three times. One-hour-long erosion experiments were carried out with the soil in a moist condition on the 23rd, 34th and 35th days. The same spray nozzle was used in the first three experiments, and in the fourth we used a nozzle that generated drops with a median diameter of 2.7 mm, rainfall intensities averaging 133 mm h^{-1}, and a kinetic energy of 19 J m^{-2} mm^{-1} (Dunne et al., 1980). The schedule of erosion experiments and non-erosive water applications is summarized in Table 2.

A more limited experiment was carried out on the Athi-Kapiti Plains where the plant cover averaged 72%, while basal cover, measured by clipping the plants back to the stalks and root tops at ground level, averaged 36%. On plots 15–17 we simulated trampling under three stocking densities above the background rate of 0.286 cow-equivalent years ha^{-1} on plot 18 (Table 1). Then we measured the response of vegetation, infiltration, and soil loss under two artificial rainstorms on three of the plots (Table 2). For the first application, the smaller spray nozzle was used on dry antecedent conditions, and the larger nozzle was used for the second experiment 2 h later on wet soil. We did not measure plant regeneration at the Athi-Kapiti sites.

5. Relation of trampling treatments to grazing patterns

The distribution of pastoral nomadic settlements in the region was determined by the trade-off between maximizing the exposure of cattle to foraging area and the need to water every 2 days. Settlements were therefore distributed around water supplies at

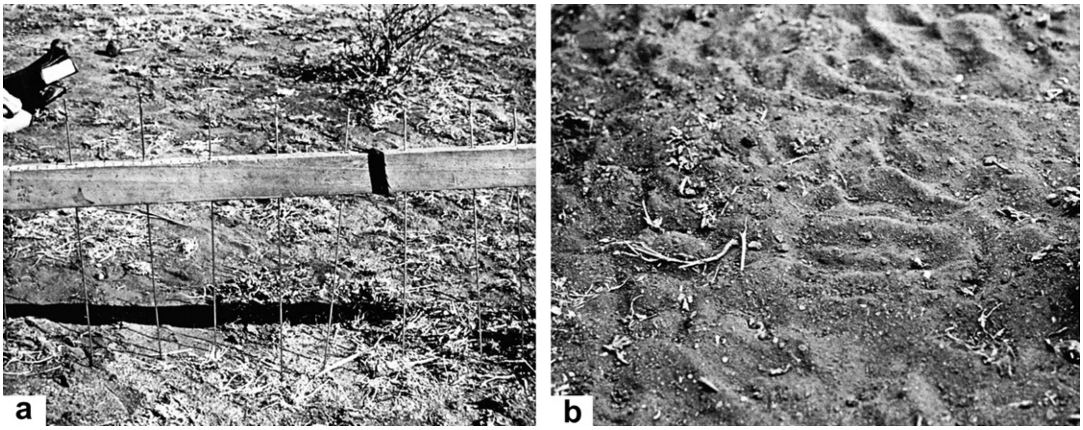

Fig. 2. Comparison of (a) the soil surface of the background plot 9 which had a plant cover density of 10% (measured with the pin-frame shown) and a light-colored sandy surface with (b) the soil surface of plot 8 after the application of 1000 artificial hoofprints m^{-2}. The plant cover density was reduced to 3.8% and the sandy surface layer was thoroughly mixed with the underlying finer-grained soil.

Table 2
Schedule of erosion experiments and non-erosive water applications on the trampled plots.

Region	Activity	Day	Average rainfall (mm)	Average infiltration (mm)
Amboseli	Trampling	0		
	1st erosion experiment	1	76	39
	Water application	7	20	20
	Water application	14	40	40
	Water application	17	40	40
	Water application	21	40	40
	2nd erosion experiment	23	67	29
	Water application	28	40	40
	3rd erosion experiment	34	77	32
	4th erosion experiment	35	134	53
	Total		534	333
Athi-Kapiti	Trampling	0		
	1st erosion experiment	1	66	65
	2nd erosion experiment	1	130	95
	Total		196	160

a distance of a half-day walk (Muchiru et al., 2008; Western and Dunne, 1979; Western and Finch, 1986).

We used field measurements (Western, 1975) of the average distance, D, walked by cattle (1950 km yr^{-1} on the dry-season range at Amboseli and 3300 km yr^{-1} over longer periods at Athi-Kapiti), the average stride length, L, of a cow (0.5 m) which we measured, two hoofprints per stride length, and the average stocking density, S, (0.125 cows ha^{-1} over 8 months yr^{-1} at Amboseli, 0.286 cows ha^{-1} over 12 months at Athi-Kapiti) to calculate the average annual trampling intensity (T_{ave}, hoofprints m^{-2} yr^{-2}) for this background stocking density (Table 1). The relation between average stocking density, distance walked, and annual trampling intensity is

$$T_{\text{ave}}\left(\frac{\text{hfpts}}{\text{m}^2\text{yr}}\right) = S\frac{(\text{cows})}{(\text{ha})}\cdot\frac{(\text{ha})}{10^4(\text{m}^2)}\cdot D\frac{(\text{km})}{(\text{yr}-\text{cow})}\cdot\frac{10^3(\text{m})}{(\text{km})}\cdot\frac{\text{stride}}{L(\text{m})} \times\cdot\frac{2(\text{hfpts})}{(\text{stride})} = \frac{0.2DS}{L} \tag{2}$$

Plots 9 and 18 were maintained in the background condition while plots 6, 7, 8, 15, 16 and 17 were subjected to various levels of simulated trampling above the backgrounds.

The elevated trampling intensities could be converted to equivalent stocking densities through the use of Equation (2) (Table 1).

If cattle are regularly herded towards a single watering point such as a borehole from a circle of settlements at a distance R from the well (Fig. 3a), the local trampling intensity, $T(r)$, rises as distance from the well, r, decreases. In the region, herds were grazed towards and away from water sources on alternate days (the calculation for other watering frequencies is straightforward). The total number of hoofprints put down in the catchment of the borehole is $T_{\text{ave}}4\pi R^2$. The constant number of hoofprints put down in each annulus of infinitesimal width dr is

$$2\pi rT(r)\mathrm{d}r = 2\pi RT(R)\mathrm{d}r. \tag{3}$$

So,

$$T(r) = T(R)\frac{R}{r} \tag{4}$$

The sum of these hoofprints as the cows travel from the perimeter of the water source's catchment at 2R to the well (of negligible radius) is

$$\int_0^{2R} 2\pi rT(r)\mathrm{d}r = 4T_{\text{ave}}\pi R^2 \tag{5}$$

Substituting (4) into (5),

$$2T(R)\int_0^{2R}\mathrm{d}r = 4T_{\text{ave}}R \tag{6}$$

which integrates to

$$T(R) = T_{\text{ave}} \tag{7}$$

Substituting $T(R)$ into Equation (4) above

$$T(r) = \frac{T_{\text{ave}}R}{r} \tag{8}$$

This predicted variation of trampling intensity as a function of $1/r$ is supported by the observations of Georgiadis (1989, Equation (1)), who used the spatial density of cattle dung as a measure of use intensity around such a watering site near Amboseli. In the case of Amboseli, where the average walking distance per day translates to $R \approx 4$ km, if r is expressed in km Equation (8) becomes

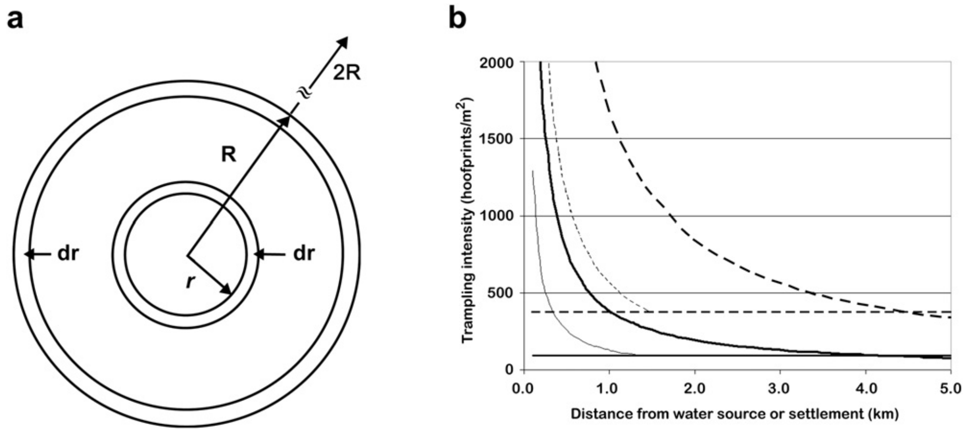

Fig. 3. Model of the spatial concentration of trampling intensity with distance r around a water source accessed from a ring of settlements at distance R. (a) Schematic diagram of the problem; (b) predicted variation of trampling intensity with distance from point and linear water sources at Amboseli (thick solid curves) and Athi-Kapiti (thick dashes), predicted from Equation (7). The thinner curves indicate the trampling intensity around each of six settlements surrounding a water source at distance R in each of the two regions, extending out to a distance at which the background trampling intensity is encountered.

$$T(r) = \frac{0.2DSR}{Lr} = \frac{390}{r} \tag{9}$$

and the treatments of the plots simulate trampling intensities approximately at 4, 3.6, 2.0, and 0.35 km from the watering point (Fig. 3b). In the case of Athi-Kapiti ($R \approx 4.5$ km), the relationship is $T(r) = 1698/r$ and the simulated trampling intensities relate to distances of 4.5, 4.4, 3.6, and 1.2 km from the well. If cows walk from a line of settlements to a line source of water (a stream), then the average trampling intensity at Amboseli would be 97 hoofprints m^{-2} everywhere, and the analogous value for Athi-Kapiti would be 377 hoofprints m^{-2} (Fig. 3b).

There is also a concentration of trampling around each settlement. It can be estimated by means of the reasoning used to develop Equation (8), but with multiplication by $2/n$, where n is the number of settlements served by a water source with a 2-day frequency. The thinner curves on Fig. 3b indicate the trampling intensities around each of six settlements out to a distance at which the background average trampling intensity is attained (1.33 km at Amboseli and 1.5 km at Athi-Kapiti).

6. Results

6.1. Effects on vegetation cover and primary production

Simulated trampling decreased the ground cover at both locations (Fig. 4) with the most intense trampling causing severe mechanical damage to both stalks and roots; some of the roots were torn out of the ground. Standing crop decreased in a manner similar to that of cover density (declining from 8 g m^{-2} under 0.125 cows ha^{-1} to 3 g m^{-2} under 1.4 cows ha^{-1} at Amboseli, and from 79 g m^{-2} to 40 g m^{-2} under 0.286–1.04 cows ha^{-1} at Athi-Kapiti). Although the proportional change was greater at Amboseli, it represented the loss of a much smaller biomass.

Fig. 5 shows the pattern of vegetation re-growth during the period of irrigation. Although a few green shoots appeared from seeds within 2 days after the first water application, recovery was slow on all plots for at least the first 21 days. In our experiments an average of 167 mm of water was applied to the plots and 139 mm infiltrated in the first 21 days (Table 2). Thereafter the growth rate increased on all plots. A single bare patch covering 20% of the background Plot 9 (97 hoofprints m^{-2} in Fig. 5) was responsible for the lower rate of recovery there. Otherwise, all plots but the most heavily trampled one reacted in a similar manner and all had approximately the same cover (23–27%) at the end of the experiment, whereas the maximum cover density measured on Plot 8 (1097 hoofprints m^{-2} in Fig. 5) was only 10%.

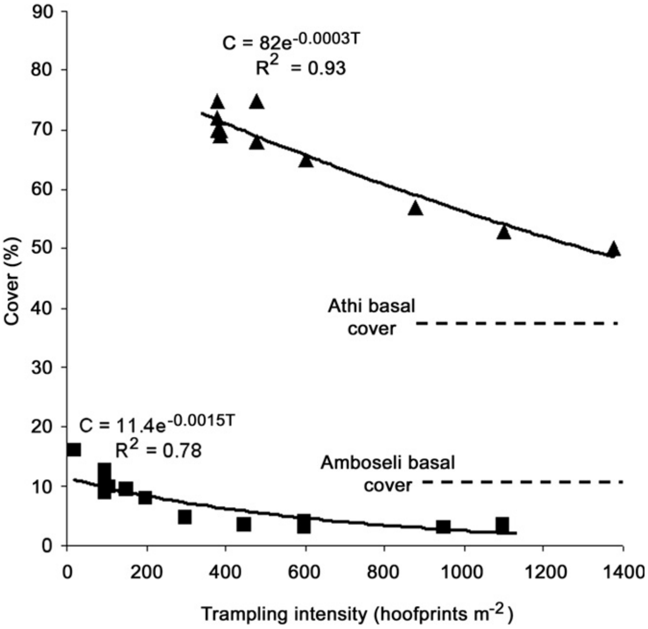

Fig. 4. Effect of trampling intensity on grass cover: at Amboseli (squares) and on the Athi-Kapiti Plains (triangles). On the heavily treated plots, trampling was interrupted several times for the measurement of cover. At Amboseli, a second plot, not used for erosion experiments, was also used for cover measurements under 500 extra hoofprints m^{-2}.

The recovery of standing crop, which was equal to production since there was no off-take during the 35 days of growth, followed the same general pattern. The standing crop rose to only 14 g m^{-2} on the most heavily trampled plot by the end of the experiments, but ranged from 40 g m^{-2} to 46 g m^{-2}, averaging 43 g m^{-2}, on the other three plots.

6.2. Effects on soil surfaces

At Amboseli, the soil surface at the end of a wet season and before artificial trampling was covered with a discontinuous 2–5 mm-thick, sand-rich layer that was significantly coarser than the underlying soil (Fig. 6). The surface layer contained only a small proportion of silt-clay (<0.062 mm) and an elevated sand content compared with the underlying topsoil. The artificial trampling sheared and scraped this surface layer, and the underlying fine-grained material was churned to the surface by the backward motion and construction of a small ridge of soil behind each hoofprint. As the four erosion experiments proceeded, each plot showed a tendency for the re-establishment of the sandy layer as fine particles were winnowed by runoff (Fig. 7).

During similar experiments on nearby plots on the same hillslope and soil type we observed that the layer shown in Fig. 6a develops as a result of the selective removal of finer particles. Although the sand grains in the layer are mobile under the combined action of raindrop impact and flow, they travel more slowly than the underlying silt and clay particles which are splashed upward through the surface layer, and the effect of the sand concentration at the surface is to reduce soil transport rates (Dunne and Aubry, 1986), as will be illustrated in

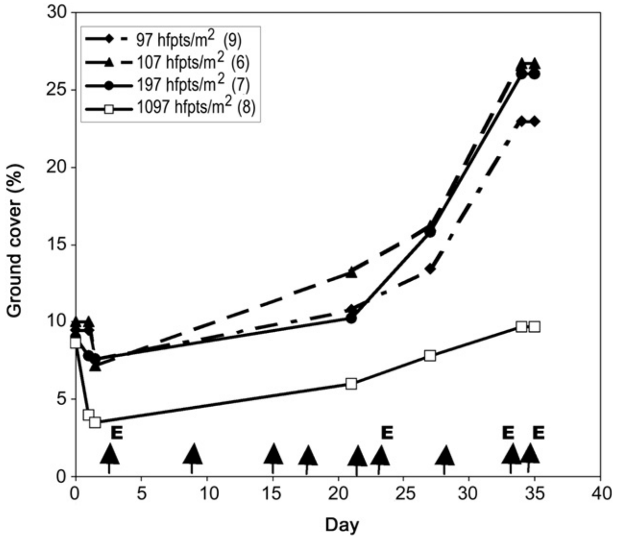

Fig. 5. Regeneration of ground cover on Amboseli plots subjected to various intensities of trampling. The values in parentheses in the legend are plot numbers. *E* on a vertical arrow indicates the time of an erosion experiment, and the other vertical arrows denote watering with a non-erosive spray, which generated no runoff.

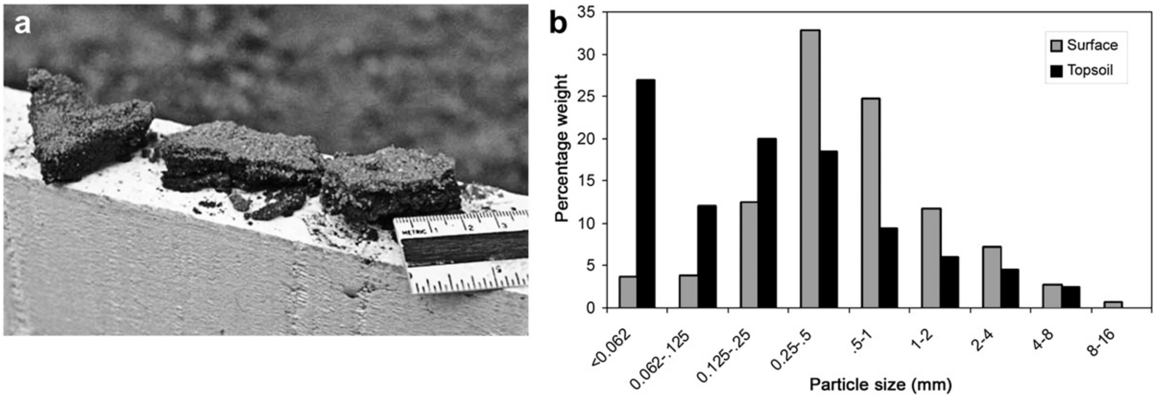

Fig. 6. (a) Sandy surface layer developed after a series of four artificial rainfall experiments on a similar plot on the same hillslope and soil on Eremito Ridge. (b) Grain-size composition of the topsoil (upper 10 cm) at the experimental site and of the 5 mm-thick armor layer (average of 9 samples scraped from the surface in the vicinity of the plots) on the Luvisol after erosion and selective transport during a wet season. Grain-size distributions were quantified by wet sieving.

Section 6.4. The sandy layer had been disturbed by the background level of trampling but was still recognizable at the beginning of our experiments.

On the Athi-Kapiti Plains, the surface of the Vertisol before artificial trampling was covered with sand- and pebble-size aggregates of silt and clay. These aggregates were broken by compression and shearing during the trampling. However, the soil disturbance was confined to a shallower layer than at Amboseli, because the underlying dry Vertisol was harder and more cohesive than the Amboseli Luvisol, and also because the denser vegetation cover and root mat absorbed a portion of the trampling stress.

6.3. Hydrological effects

For the Luvisol at Amboseli, the infiltration rates (i) are plotted against the corresponding rainfall intensities (I) in Fig. 8. The relationship

$$i = -1.0 + 0.37I \tag{10}$$

yielded $r^2 = 0.90$ ($n = 25$; $p < 0.0001$) over the range $45 < I < 183$ mm h^{-1}. Neither trampling intensity nor plant cover was significantly correlated with infiltration rate, and neither of these measures significantly increased the explained variance over Equation (10) in a stepwise multiple regression. Values from the least

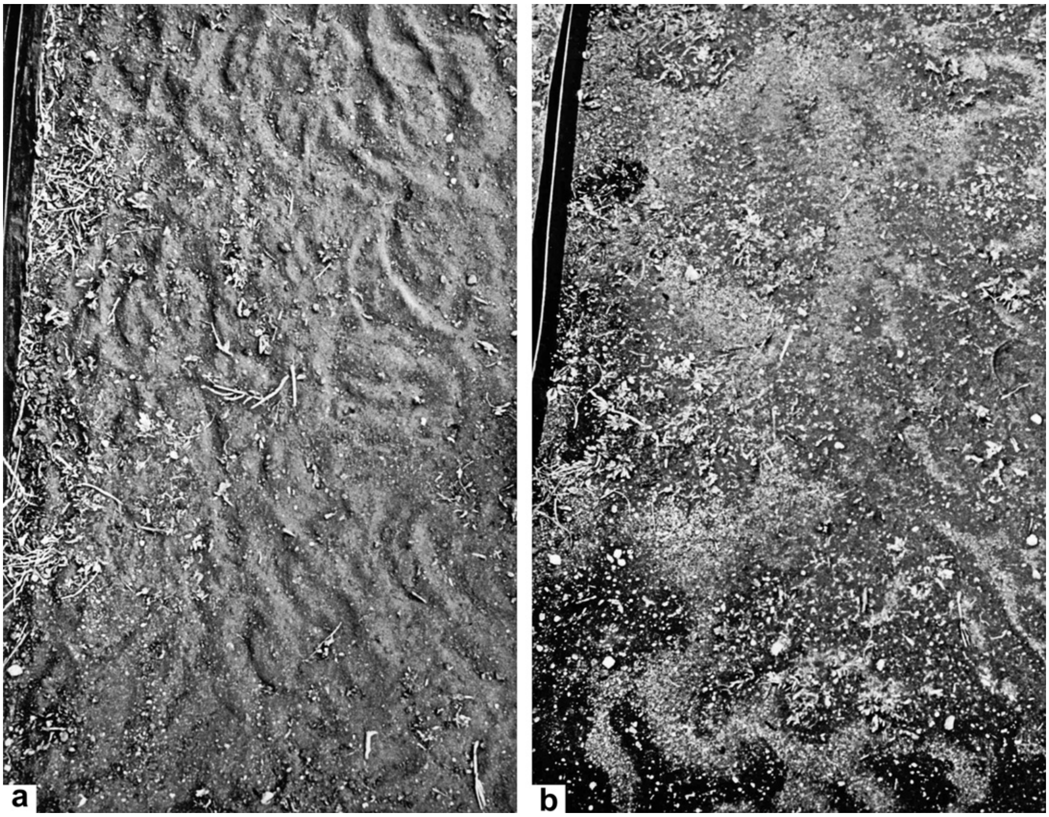

Fig. 7. Comparison of the surface of plot 8 after trampling with the same surface after the fourth erosion experiment showing partial re-establishment of a lighter colored, sandy surface layer.

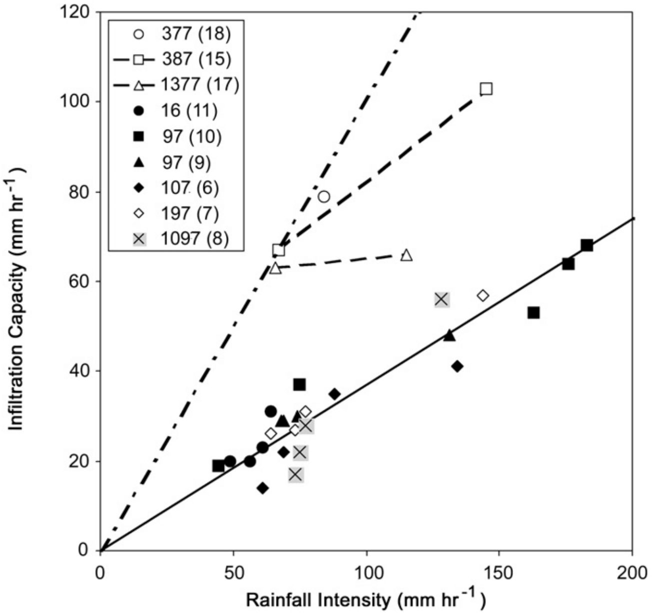

Fig. 8. Variation of measured infiltration rate (i) with rainfall intensity (I) for the plots at Amboseli (solid symbols and regression line) and on the Athi-Kapiti Plains (open symbols and dashed lines). The numbers listed for each plot indicate the intensity of simulated trampling in hoofprints m^{-2}, and the plot numbers are in parentheses.

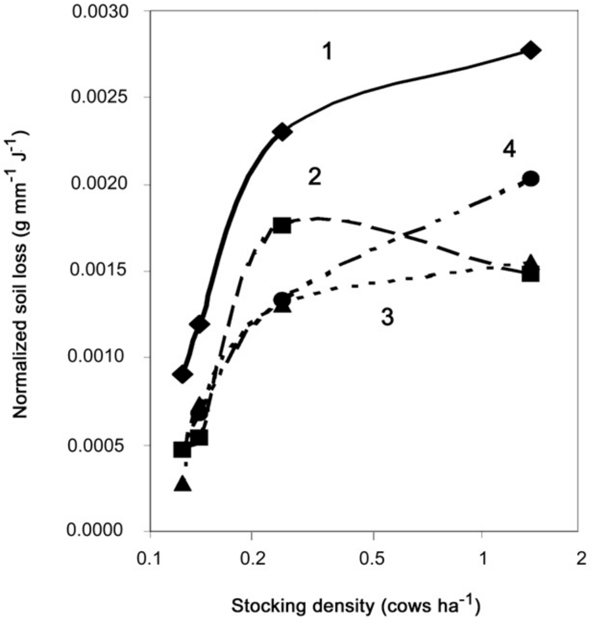

Fig. 9. Influence of trampling intensity on normalized soil loss during each set of Amboseli experiments, the order of which is indicated by the numbers on the curves; 1–3 denote experiments conducted with the smaller nozzle, while the larger nozzle was used for the fourth set of experiments. Normalized soil loss is the mass of soil eroded (g m^{-2}) divided by the volume of runoff (mm) and the kinetic energy of the rainfall (J m^{-2}). The curves joining points indicate experimental sequences, not interpolation of values.

heavily trampled plot 11, stocked only by wildlife, do not show any consistent difference from the more heavily trampled plots (Fig. 8).

The small number of experiments and the complexity of events during simulated rainfall on the clay-rich soils with shrinkage cracks on the Athi-Kapiti Plains makes the interpretation of these infiltration results (Fig. 8) more complex, as explained in Section 7.2. On plots 15 and 17, which were irrigated twice, the infiltration rate increased from the first to the second (more intense) rainfall application, despite the fact that the shrinkage cracks had begun to close as the soil became wetter. However, infiltration rate declined as trampling intensity increased and plant cover declined from plots 18 and 15 to plot 17 (Fig. 8). Since the dry soil was very hard at the time of trampling, we saw no signs of compaction, but we observed three trampling-related processes that contributed to lowering the infiltration rate. First, the loose pebble-sized aggregates on the soil surface were crushed and sheared by the trampling, providing fine particles that sealed surface pores and cracks during rainfall. Secondly, trampling abraded the edges of cracks, and the loosened soil fell into the cracks, which therefore closed sooner during rainfall as the filling material became wet and swelled. Thirdly, the trampling-related reduction in plant cover density from 75% to 50% decreased the hydraulic roughness of the runoff (see Fig. 3a in Dunne and Dietrich, 1980b for an example of this effect when cover density was reduced from 77% to 36% on a nearby plot). The lowered hydraulic roughness decreased flow depth at a constant runoff rate, causing less of the runoff to inundate the more permeable microtopographic highs or to spill across microtopographic divides and into open cracks.

6.4. *Effects on soil loss*

The curve labeled 1 in Fig. 9 illustrates the normalized soil loss (g mm^{-1} J^{-1}) during the first rainstorms with a median drop size of 2.0 mm on Amboseli plots 6–9. Measurements of each factor affecting the soil loss in the experiments are listed in Table 3. At the end of the first set of artificial rainstorms the surface of the lightly trampled plots retained pale, continuous, sandy armor layers, whereas the heavily disturbed plots 7 and 8 had only thin, discontinuous patches of sand at the surface. During later erosion experiments, these patches spread and thickened (Fig. 7b). The second set of experiments (curve 2 in Fig. 9) produced a sharp decline in normalized soil loss even though the vegetation cover had increased by only 1–3% (Fig. 5). The third set of experiments yielded almost the same normalized soil-loss values as the second set, except for plot 7, despite the fact that the vegetation cover had increased dramatically on each plot between the second and third set of experiments (Table 3, Fig. 5). The fourth set of experiments with the larger nozzle (median drop size = 2.7 mm) caused a reversal in the trend of normalized soil-loss rate on two of the plots. Fig. 10 expresses the normalized soil-loss rate from the three experiments with the smaller nozzle size as a function of both cover density and experimental sequence for the four stocking rates.

On the Athi-Kapiti plots, normalized soil-loss rates from the first set of artificial rainstorms (median drop size 2.0 mm) were lower than the first experiments at Amboseli on much sparser covers for comparable trampling intensities (Table 3). Most of the sediment mobilized by rainsplash and sheetwash was washed into open cracks (~1 cm wide) in soil surface. During the subsequent simulations with the larger nozzle, soil-loss rate increased from the lightly trampled plot 15, which had yielded no measurable soil in the dry-soil run, but decreased on the heavily trampled plot 17 despite the fact that shrinkage cracks were visibly less open in the wetter soil and the raindrops were larger.

7. Discussion

7.1. *Effects on vegetation cover and primary production*

The highest trampling intensities simulated in our experiments were equivalent to those expected to occur 0.35 km from a water source and 0.12 km from a settlement at Amboseli, and 1.2 km from

Table 3
Summary of runoff and soil loss from the sequence of hour-long experiments on each plot. The sequences of experimental and antecedent conditions are described in the text. Normalized soil loss is the total soil eroded per m^2 of the plot divided by the total runoff and by the kinetic energy of the applied rainfall per m^2 of the plot.

Region	Plot No.	Trampling intensity (hoofprints m^{-2})		Stocking rate (cow ha^{-1})	Experiment	Plant cover (%)	Rainfall (mm)	Runoff (mm)	Soil loss (g m^{-2})	Normalized soil loss (g mm^{-1} J^{-1})
		Artificial	Total							
Amboseli	9	0	97	0.125	1	10	79	34	44	0.0009
					2	11	68	38	22	0.0005
					3	23	74	40	15	0.0003
					4	23	131	78	91	0.0005
	6	10	107	0.14	1	10	69	39	58	0.0012
					2	13	61	37	22	0.0005
					3	27	88	48	56	0.0007
					4	27	134	84	145	0.0007
	7	100	197	0.25	1	8	77	37	118	0.0023
					2	10	64	33	67	0.0018
					3	26	73	42	72	0.0013
					4	26	144	85	310	0.0013
	8	1000	1097	1.41	1	4	77	39	150	0.0028
					2	6	75	44	88	0.0015
					3	10	73	50	102	0.0016
					4	10	128	77	380	0.0020
Athi-Kapiti	18	0	377	0.286	1	73	88	3	5	0.0010
	15	10	387	0.29	1	70	67	Trace	Trace	Trace
					2	70	145	31	51	0.0006
	17	1000	1377	1.04	1	50	66	1	2	0.0017
					2	50	115	40	105	0.0012

a water source and 0.4 km from a settlement at Athi-Kapiti, according to Equation (8). The relations between cover and trampling intensity in Fig. 4 must be extrapolated to estimate effects closer to concentration points, especially in the case of Athi-Kapiti. With this extension, the equations in Fig. 4 predict reduction of late-dry-season cover at Amboseli from a background of ~10–~6% at 1 km from water and to <1% at 0.1 km, whereas the analogous values for Athi-Kapiti are from a late-dry-season background of ~73–~49% at 1 km and <1% at 0.1 km. The implication of these cover reductions for erosion during the succeeding wet season will be apparent from Section 7.3.

When the cover densities thus computed were inserted into Equation (1) and the biomass of standing crop, $M(r)$, was calculated for a 2 cm high plant cover at various distances from the water source, there was a strong decline towards each center. However, when the equation for $M(r)$ was integrated from $r = 0$ to $2R$, the resulting reduction in standing biomass was only ~1–2% of that in the grazing catchment of each water source in both cases. Biomass around a total of 6 settlements would also be reduced by ~4% of the total plant biomass within the circle of 8 km at Amboseli but only 0.25% within 9 km of a water source Athi-Kapiti.

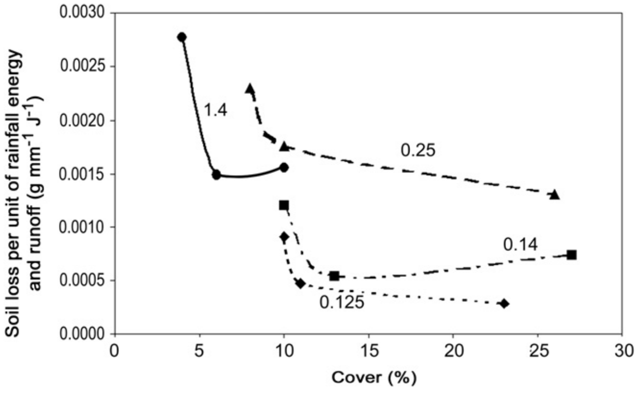

Fig. 10. Variation of normalized soil loss with cover density at Amboseli during sequences of three 1-h artificial rainstorms with a median drop size of 2.0 mm for each of the simulated stocking intensities (indicated by the labels on the curves). The larger drop size in the fourth experiment caused an increase in normalized soil loss for only two of the plots (Table 3). The curves joining points indicate experimental sequences, not interpolation of values.

Trampling at stocking densities at least twice the background rate did not lower the density to which the grass at Amboseli recovered at the end of the simulated wet season, but further intensification of trampling caused a strong decline in rejuvenated cover, at least in this drought period when the root stocks of plants had been reduced by water stress and heavy grazing and trampling. The recovery of production followed a similar pattern with severe reduction in recovery to one-third of the mean value for the other plots being observed only after the most intense trampling. The >21-day lag in the recovery of cover density and above-ground production is generally consistent with Scott Russell's (1977) description of work by Garwood and Williams (1968) showing that rapid growth in rye grass began a few weeks after the addition of ample water following a period of intense water stress. At a larger scale, satellite and field observations of vegetation in the Sahara Desert, the Sahel, East Africa, and Israel have shown that vegetation cover increased in response to rain after a few weeks to 3 months (Herrmann et al., 2005; Linderman et al., 2005; Nicholson et al., 1990; Schmidt and Karnieli, 2000). We were unable to measure the response of recovery and production to trampling intensity at the wetter Athi-Kapiti site.

7.2. Hydrologic effects

On the dry-season rangelands, trampling above the background level tended to shear and churn the soil surface rather than compact it. Thus, compaction due to trampling at intensities above the wildlife-only case of plot 11 (Fig. 8) did not diminish infiltration rate. Greene et al. (1994) found the same result in a rangeland of similar soil and rainfall in Australia. At Amboseli, the changes in plant cover density during re-growth had no recognizable effect on infiltration capacity because they involved mainly changes in the aerial components of the plants rather than in the extent or density of the roots over the 35 days of the watering experiment. This situation might change over several years of intensified or reduced trampling. Rainfall intensity had an important effect on the measured infiltration rates at Amboseli for two reasons, analyzed more fully by Dunne et al. (1991): (a) increasing the rainfall intensity brought increasing proportions of a plot to saturation and therefore increased the spatially averaged water intake rate; and (b) intensifying the rainfall increased the rate and depth of runoff and therefore inundated a larger proportion of the vegetated microtopographic protuberances which had higher concentrations of macropores than did the intervening depressions.

At Athi-Kapiti, infiltration rate increased under the higher rainfall intensities, despite the shrinkage cracks beginning to close, because of the two effects described above. However, on the most heavily trampled plot, two other effects intervened to limit the increase. First, the intense trampling created more mobile soil (Table 3), most of which was observed to enter cracks where it swelled to accelerate their sealing. Secondly, the reduction of the vegetation cover by trampling on plot 17 from 73% to 50% reduced hydraulic roughness and therefore flow depth (Dunne and Dietrich, 1980b) and infiltration rates (Dunne et al., 1991). At Amboseli, the vegetation cover was so sparse that the small reduction by trampling did not affect the hydraulic resistance enough to reduce infiltration rates. More detailed and intensive studies of the effects of trampling on the hydrologic properties of densely vegetated Vertisols are needed to separate the direct effects of trampling on soil properties from the indirect effect of reducing the hydraulic roughness of a thick vegetation cover.

7.3. *Soil loss*

The increase in normalized soil loss with stocking density in the first set of rainfall simulations at Amboseli (curve 1 in Fig. 9) was associated with both the small decrease in vegetation cover from 10% to 4% over the range of stocking rate from background to heavy, and with the disruption of the sandy surface layer and the delivery of fine sediment to the surface, as described in Section 6.1 and illustrated in Fig. 2. Intensified splashing of fine sediment into the runoff was clearly visible from the freshly trampled areas of even the more lightly trampled plots. It is not yet clear whether trampling the surface only 1 day before a rainstorm renders it more erodible than a soil that has been trampled days or weeks earlier and then subjected to eolian rearrangement or removal of finer particles from the surface. This uncertainty does not diminish the internal comparability of the results in Fig. 9. Even the slight extra disturbance caused by 10 artificial hoofprints m^{-2} on plot 6 as compared to plot 9 (equivalent to a 12% increase in stocking rate from 0.125 cows ha^{-1} to 0.14 cows ha^{-1}) without any change in vegetation cover produced a measurable acceleration of erosion. Increasing the artificial trampling level to 100 hoofprints m^{-2} on plot 7 (0.25 cows ha^{-1}) to represent a doubling of stocking density over the background level more than doubled the rate of soil loss, even though vegetation cover declined only from 10% to 8%. Soil loss was most sensitive to trampling intensity at stocking rates of up to about 0.25 cows ha^{-1}. Beyond this level, plant cover could decrease only slightly with increased trampling intensity (Fig. 4a and Table 3), and though the continued shearing of the surface produced a deeper layer of loose soil, it did not radically increase the amount of fine-textured soil exposed to transport.

The reductions in soil loss in later experiments were associated mainly with the re-establishment or augmentation of a sandy surface layer (Fig. 6) before the re-establishment of significant plant cover. The intensity of trampling was still reflected in the soil loss even during the fourth set of experiments. For example, plot 7 (0.25 cow ha^{-1}) had a normalized soil-loss rate 2.8 and 2.0 times those of plot 9 (background) and plot 6 (lightly trampled) respectively even though it had essentially the same plant density (26% versus 27 and 23% respectively). This result indicates that the effects of trampling on soil-surface texture can persist through an erosive wet season, even if vegetation recovers from the mechanical damage due to trampling. The most heavily trampled plot responded most sensitively to an increase in runoff and kinetic energy in the fourth experiment because of its larger surface reservoir of churned fine sediment.

The landscape-scale impact on erosion due to the concentration of trampling between the settlements and a water source at Amboseli was estimated as follows. An erodibility ratio, E, of normalized soil loss in each experiment relative to the soil loss on the background plot was calculated for each experimental sequence (from data in Table 3) and plotted against its appropriate distance from the water source, calculated from the trampling intensity using Equation (8). A second-order polynomial was fitted to the four points thus obtained for each experimental sequence. This function, $E(r)$, was then integrated from $r = 0$ to R to produce a measure of the change in erodibility over the grazing domain between water source and settlement. When compared with the erodibility for the background condition ($E = 1.0$) applied to the entire grazing catchment of the water source (area $= 4\pi R^2$), this integral yielded a measure of the degree to which the erodibility of the entire area was increased at each stage in the sequence of trampling and surface re-establishment.

The area-weighted erodibility of each water source catchment increased by a factor of 1.25 for the conditions immediately after trampling, 1.28 after the second rainfall (using a linear erodibility gradient), 1.66 after the vegetation recovery, and fell back to 1.31 in the most intense rainstorm on the recovered vegetation. The added analogous effect of trampling out to the background level around 6 settlements served by a water source was to increase the area-weighted erodibility of the entire grazed catchment by factors of approximately 1.42, 1.46, 2.08, and 1.51 (ignoring a small amount of overlap between the calculations for the water source and each settlement). The index increased because the trampled plots recovered their resistance to erosion through the establishment of a sandy armor layer more slowly than the background plot. The most heavily trampled surface (representing conditions closest to the water source and settlements) recovered its resistance at the slowest rate. In the largest rainstorm even the background plot suffered intensified erosion. Thus the area-weighted change in erodibility of the trampled surfaces is more sensitive to trampling than are the changes of primary production, and they increased the average erodibility of a grazing catchment served by each point water source by 25–108% for the conditions simulated in Amboseli.

Fig. 10 indicates that in the Amboseli experiments there was a general inverse relationship between normalized soil loss and plant cover as the vegetation responded to trampling and regrowth. This result is consistent with the results of many summaries of rangeland erosion, such as those by Castillo et al. (1997) and Goff et al. (1993). However, in these experiments the relationship was complicated by the stronger, direct effect of mechanical mixing of the sandy surface layer with the underlying finer soil. Increases in plant cover of 1–3% between the first and second experiments were accompanied by 22–58% reductions in normalized soil loss. More than doubling plant cover between the second and third experiments was associated with smaller (0–25%) reductions in normalized soil loss.

Thus, a broader implication of Fig. 10, especially in light of the time required for vegetation to respond to rainfall (Fig. 5) is that on soils with a range of particle sizes sufficient to develop armor layers during sequences of runoff events this armoring mechanism limits erosion rates throughout most of the wet season before vegetation cover density can exert an influence. Plant cover increases only late in the wet season, and is then reduced by grazing and trampling during the dry season. Trampling during the dry season once again disrupts the armor layer, preparing it for erosion during the early part of the next wet season. This is not to suggest that vegetation cover plays no part in reducing erosion in dry-season rangelands, but only that analyses of rangeland erosion, especially around concentration points, need to take account of the seasonality of grazing and the mechanics of surface armoring by a relatively coarse-textured layer and its disruption by trampling.

Although too sparse to be convincing by themselves, the soil-loss data from the Athi-Kapiti Plains were consistent with the interpretation of the Amboseli experiments in that the normalized soil loss diminished between the first and second experiments on the most heavily trampled plot as soil loosened by trampling was washed into cracks reducing the amount available for transport in the second, larger rainstorm. The infiltration capacities of the dry, cracked soil were so high compared to rainfall intensities measured at nearby Wilson airport, Nairobi (Lawes, 1974), that runoff early in the wet season is improbable. However, as discussed in Section 7.2, the greater soil mobilization on the heavily trampled plot contributes to the large reduction of infiltration capacity apparent in Fig. 8, thereby increasing the probability and amount of runoff as the soil becomes wetter and the cracks close in each wet season.

8. Conclusion

Trampling intensity above average background levels increases as grazing animals converge on water sources, settlement sites, access corridors, and late-dry-season concentrations of forage such as swamps and floodplains. The degree of intensification varies with stocking rate and the distance from settlement to concentration point. In dry-season rangelands, the intensification decreases cover and standing crop biomass, and the shearing action of hooves overturns relatively coarse soil particles that have been concentrated into an armoring layer during previous runoff events, mixing finer particles back to the surface where they increase erodibility. The magnitude of these effects varies with soil type and vegetation cover in ways that we have measured under experimental conditions.

We have generalized our plot-scale findings to landscape scale by proposing a simple mathematical model of trampling patterns and some empirical relationships between trampling intensity, vegetation response and erodibility. The effect on region-wide erodibility is much greater than on vegetation.

The effects of trampling on infiltration and runoff are more complex and more difficult to generalize about. They appear to be small on dry-season rangelands because the shearing action of hooves has a more obvious effect on surface character than does compression, although compression is likely to be a more important process on rangelands that become grazed for the first time after woodland removal for fuel harvest (for example Dunne, 1981). On soils with shrinkage cracks some effects of trampling on infiltration capacity were measured, but their hydrologic significance as the infiltration capacity of such soil evolves during a wet season remains to be quantified.

The approach we have illustrated can be applied to other herding strategies to assess the impact of concentrated trampling resulting from the development of water sources, sedenterization, and other forms of intensive grazing management. It would be useful to quantify the effects of plant consumption on productivity, hydrology, and erodibility in terms that could also be linked to cattle mobility under various herding practices.

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