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The cow as a geomorphic agent — A critical review

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Abstract

Cows are important agents of geomorphological change. On the uplands, heavy grazing compacts the soil, reduces infiltration, increases runoff, and increases erosion and sediment yield. However, light and moderate grazing have effects that are much less significant. In riparian zones, grazing decreases erosional resistance by reducing vegetation and exposing more vulnerable substrate. Trampling directly erodes banks, thus increasing turbulence and consequent erosion. Future studies should be framed within the hydroclimatological, edaphic and geomorphological dimensions of the areas being studied so that controlling variables may be more readily isolated. We believe that both empirical studies and deterministic modeling can provide insights as to the effects of grazing on geomorphology.

1. Introduction

Many lacunae exist in the emerging field of biogeomorphology and the role of fauna at all levels needs far more research (Viles, 1988; Trimble, 1988, 1994). A forthcoming and welcome contribution in this area is *Zoogeomorphology* by D.R. Butler (1995), in which emphasis is placed on the role of feral animals. In this paper, we review the role of a large ubiquitous mammal, the cow (order: *Artiodactylas* fam: *Bovidae*). Between 1940 and 1990 the number of cattle in the United States increased 60%. This increase took place predominantly in the west, where the number of cattle more than doubled from approximately 25,552,000 to 54,445,000 (U.S. Census of Agriculture). Coincident with this change, private acreage in pasture or rangeland was reduced some 15%. These figures do not include the public domain used for grazing, primarily in the west. The largest reductions took place in the east, where private land used for pasture or rangeland decreased from approximately 160,000,000 to 87,460,000 acres (U.S. Census of Agriculture). This is due, in part, to the curtailment of grazing in eastern woodlands. It thus appears that more cattle are grazing less land but the increase of feedlots and confinement dairying make exact densities difficult to compute. Even though there have been improvements of grazing management, the increases of cattle suggest that grazing impacts will continue into the foreseeable future.

We recognize that other large animals are important agents of geomorphic change, but we restrict the discussion to cattle because they appear to be most widespread and more literature exists about them. While there is much transfer of this information to the effects of other animals, there are important differences. For example, mule deer, elk and horses are individually much more destructive to upland habitats than are cattle (Hungerford, 1980). On the other hand, cattle have greater impacts on riparian environments (Platts, 1991).

Although a considerable literature exists, the focus has been primarily on agriculture and environmental management. Our sources are the published literature and many years of observation. We hope to give more

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of a geomorphological focus and our intent in this limited format is not so much to show what is known, but to help fill some minor gaps and suggest some potential research questions and directions.

Our framework of discussion is to examine the effects on force and resistance and we divide those further into direct and indirect effects. We look first at upland slopes and then at streams and ponds. Our focus is primarily fluvial.

2. Uplands

Before studies of upland grazing impacts on soil compaction, infiltration and runoff are discussed, it is appropriate to briefly note the widely varied definitions and methodologies. The greatest problem is the lack of standard definitions for grazing intensities. At the outset, we note that there can be no universal definitions of grazing intensities. These must vary by land capability, plant productivity and climate, among other variables. Strangely, few studies have mentioned such standard measures as *land capability* or *range site* as reported in USDA soil surveys.

Of 18 studies giving definitions of grazing intensity, 12 used some form of cows per acre-time, which we have converted to animal unit months per hectare (AUM ha^{-1}) (Table 1). For these data, the average value for "light" grazing is 0.65 AUM ha^{-1} with a range of between 0.17 and 1.5 AUM ha^{-1}. The average value for "moderate" grazing is about 1.2 AUM ha^{-1}, with a range of between 0.16 and 3.7 AUM ha^{-1}. For "heavy" grazing, the average is about 2.5 AUM ha^{-1}, with a range between 0.22 and 7.4 AUM ha^{-1}. The remaining six studies used varied definitions including extremely heavy short term stocking rates not convertible to AUM ha^{-1}.

Table 1
Categorization of grazing intensity in AUM ha^{-1}

Authors	Light	Moderate	Heavy
Van Haveren (1983)	0.6	0.797	1.37
Walker and Heitschmidt (1989)			0.27
Hart et al. (1991)	0.17	0.28	
Naeth et al. (1990)	1.2 to 1.5	1.6	2.4 to 4.4
Wood and Blackburn (1981)		0.16	0.22
Linnartz et al. (1966)		3.7	7.4
Rauzi and Smith (1973)	0.597	0.789	1.38
Rauzi (1963)		1.25	3.125
Sharp et al. (1964)	0.76	1.02	1.62
Abdel-Magid et al. (1987)	0.19	0.33	0.44
Hofmann and Ries (1991)	1.1	1.7	4.6
Pinchak et al. (1991)	0.169 to 0.175		

We also examined the methodologies of 30 grazing studies. Nineteen of these studies investigated infiltration and/or runoff. Of these, 8 relied on natural precipitation, whereas the remainder utilized various rainfall simulators. Several studies used flumes or catchments to collect runoff, and many used infiltrometers (concentric and double-ring) to calculate infiltration. Most of the studies were conducted on small plots within larger pastures within even larger drainage basins. For example, plot sizes included areas 62.5 cm × 40 cm, 5 m × 6 m, 50 m × 10 m, 0.6 ha, 1.7 ha, 130 ha and 190 ha. Only two studies mentioned used the watershed as their site, but the experiments appear to have been conducted on just a portion of the watershed in any event. Most of the studies used several plots to examine different treatments or grazing intensities. In some cases plots were constrained with artificial borders which can result in erroneous measurements. The majority attempted to compare the results to some sort of control plot, and a few used dual plots as replications. Many researchers noted that there were different soil types, slopes, aspects, micro-climates, etc. within the study areas. To their credit, some reports mentioned the history of grazing that occurred on the study sites, but few commented on the effects that this might have on their results.

2.1. *Compaction effects*

Most landscapes are composed of mostly upland slopes and it is here that cattle have perhaps collectively their greatest effects. They directly reshape the earth, compact the soil and cause increased runoff, sometimes transforming the runoff regime from variable source area to unsaturated (Hortonian) overland flow. They further weaken biological resistance and trample and loosen soil, changing its susceptibility to both water and wind erosion. Grazing damage to the rangelands of the western United States has historically received attention (e.g. Satterlund, 1972; Hadley, 1974; Cooke and Reeves, 1976; Sheridan, 1981; Graf, 1985, 1988).

Fig. 1. Effect of hoof shearing action on a 45° slope, Vernon County, Wisconsin, 1974. Blade in background is 12 cm wide.

The direct force of cattle hoofs reshapes the land. That force is often conceptually underestimated because it is conceived as static, i.e., the mass of the cow (typically 400–500 kg) divided by a few cm^2 of basal hoof area. But in the movement of a cow, that mass is often transferred to one or two hooves and there is acceleration in the movement. Using a mechanical simulator, Scholefield and Hall (1986) calculated that a 530 kg cow would exert 250 kPa of vertical stress while walking on level ground. However, the process is best seen and most effective when a cow is climbing a steep slope. Then, the mass is often concentrated on the downslope rear leg which propels the animal some distance upslope. No one has yet measured the acceleration, but the quickness of movement, along with the mass of the cow suggests that the total force is considerable (Force = mass × acceleration). When divided by the basal area of one hoof, the unit force on the soil becomes high indeed. Directed normal to a level slope, this may simply compact the soil, but given the lateral vector on a steeper slope, the power to shear and move soil downslope, reshaping the surface, is greatly enhanced (Fig. 1).

The most common manifestation of direct force is the path or trail. Although cows tend to range widely on a daily basis, they do use the same path enough to create trails. Being created by both compaction in the trail itself (Duce, 1918) and displacement to the sides, trails often resemble narrow, linear troughs with raised shoulders. In wet soils, they may be 30 cm deep (Hole, 1981). Scholefield and Hall (1986) note that impressions this deep are probably not created entirely by soil compression, but they suspect that such prints form in soils with high water content, where plastic flow is generated around the edges of the hoof. Because the trails are less permeable (from compaction and crusting: Rostagno, 1989) and because they conduct water, they may erode to larger proportions (Hole, 1981) even under "light" grazing (Naeth et al., 1990), and direct water and/or sediment cascades onto other, perhaps more vulnerable areas, themselves often created by the cow (Kauffman et al., 1983a, b). Cooke and Reeves (1976) speculate that concentration of runoff along such trails could help initiate downslope gully development and the work of Rostagno (1989) would appear to support such a suggestion. Upland trails are thus of great interest to the fluvial geomorphologist.

Another feature of direct force is the cow terracette or "cowtour" (Fig. 2). Although many factors may account for such steps or terracettes (Brice, 1958; Vincent and Clarke, 1979), the role of animals may be primary in some cases (Higgins, 1982; Howard and Higgins, 1987), but absent in others (Vincent and Clarke, 1982). Their effects on hydrologic processes have not yet been ascertained, but there is at least a superficial similarity to agricultural contour ridging, a practice which significantly reduces storm runoff (USDA-SCS, 1972).

Compaction is a strong direct effect of force which leads to the indirect effect of reduced infiltration and

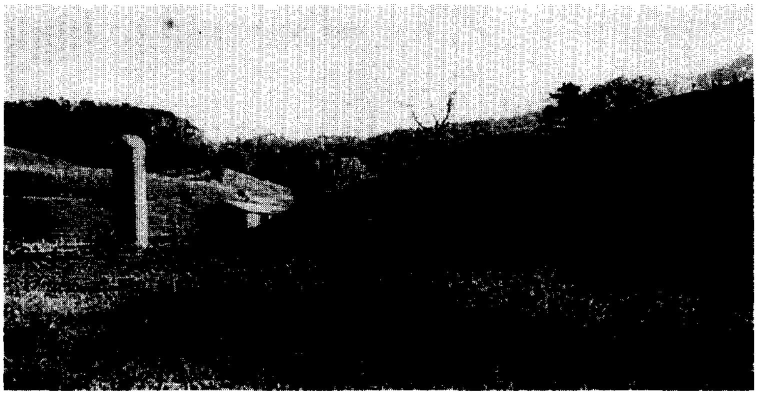

Fig. 2. Cow terracettes or "cowtours". Vernon County, Wisconsin, 1974.

the resulting force of increased overland flow, which in turn leads to increased erosion (Figs. 3 and 4). Soil compaction is especially rapid in wet soil, because wet structural particles disintegrate more easily (Proffitt et al., 1993). However, saturated soil is not as easily deformed because the porewater helps to retain soil structure (Howard and Higgins, 1987). Many studies have investigated the changes in soil bulk density due to compaction by "heavy" grazing, and several are referenced by Lull (1959), Blackburn et al. (1982), and Kauffman and Krueger (1984). Such studies continue with Tollner et al. (1990) and Naeth et al. (1990) showing that "heavy" grazing in enclosures caused significant increases of bulk density and cone penetrometer readings. Another example is a study by Orodho et al. (1990) within the Chaco Canyon drainage basin, New Mexico, which indicated that "heavy" grazing caused an 8% increase in soil bulk density (1.50 vs 1.38 g cm^{-3} in sandy loam soil). The authors note that this effect of "heavy" grazing was more evident on hilltops than in the low-lying areas, a phenomenon which may relate to the fact that grazing effects rarely occur below 25 cm soil depth (Chancelor et al., 1962). Significant changes to soil bulk density at greater depths are not as likely because the weight of the overburden itself compacts the subsurface soil (Ferrero, 1991). Thus, the shallower soils of hilltops might be expected to be relatively more affected than the deeper soils of lowlying areas.

A phenomenon related to trails and compaction is smearing. Cows having access to less-permeable plastic soils or subsoils may track these onto nominally

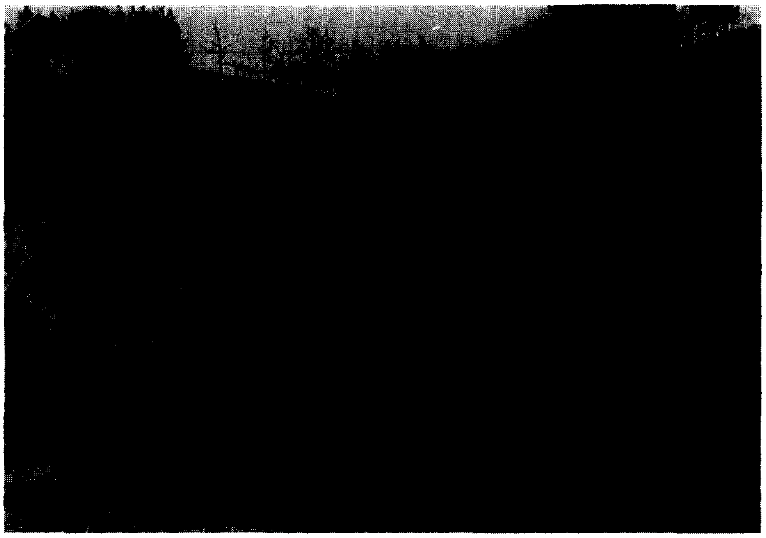

Fig. 3. Cow holding area near dairy barn. Note bare soil and discontinuous gully. La Crosse County, Wisconsin, 1991.

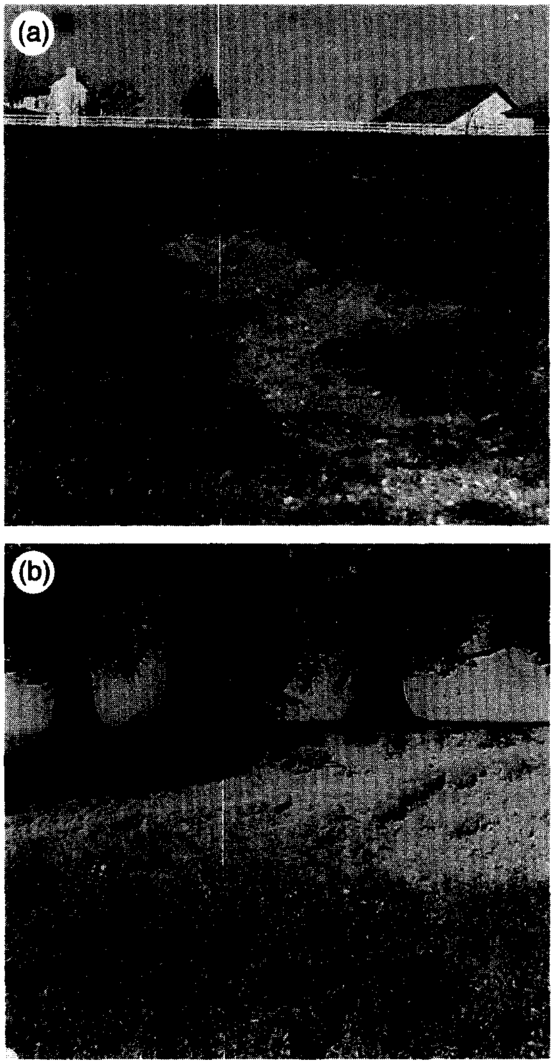

Fig. 4. Effects of overgrazing on humid region pasture. (a) Discontinuous gully, Giles County, Tennessee. (b) Lounging area, Studley Royal, North Yorkshire, 1991. Note exposed tree roots and breaks in slope profile.

more-permeable areas so that infiltration is reduced (E.M. Brick, pers. commun., 1995).

A more subtle feature of direct force on grazed slopes is the enhancement of meso–micro relief. That is, differential compaction enhances the surface roughness. This may be due to soil differences (e.g. deep vs shallow) or obstructions to compaction such as a flat rock lying horizontally within the soil profile. Consonant with grazing studies cited earlier showing increases of bulk density and higher cone penetrometer readings, we have observed grazed fields that were visibly lower (2–10 cm) than adjacent ungrazed fields, but recognize that some of the difference could have been caused by erosion from the grazed field. When surveying across such adjacent fields, we have also observed the difference in the pressure required to insert chaining pins (sharpened steel shafts of about 3 mm diameter). Whereas in the ungrazed area, especially under forest, the pins can often be inserted with the pressure of one finger, insertion on the heavily grazed site might require most of one's body weight. Under very dry conditions, we have been sometimes required to hammer the pins into the ground with a hand ax.

The foregoing discussion has dealt with diminished infiltration and increased runoff resulting from compaction of soil by cattle. In reality, much more than bulk density usually changes in response to grazing (Thorp, 1949; Reed and Peterson, 1961; Nielsen and Hole, 1964; Hole, 1981; Krausman et al., 1985; Mitchell, 1988). For example, the combination of grazing and trampling will usually reduce the density of grass cover (e.g., Hofmann and Ries, 1991). Among other effects, severe compaction often reduces the availability of water and air to the roots, sometimes reducing plant vitality (e.g., Reed and Peterson, 1961). Grass species change from perennial to annual (Kinucan and Smeins, 1992) and from deep-rooted to shallow-rooted (Naeth et al., 1990). Removal of phytomass by grazing and lessened phytomass production can reduce fertility and organic matter content of the soil. Soil aggregate stability is decreased and the surface sometimes becomes crusted. Proportion of bare soil appears to correlate well with surface runoff and sediment yield (Copeland, 1965; Lusby, 1970; Branson et al., 1981; Thurow et al., 1986; Warren et al., 1986a; Takar et al., 1990; Bari et al., 1993).

2.2. *Flora and fauna effects*

Studies by Graf (1979) and Zöbisch (1993) indicate that vegetational thresholds for soil erosion may exist. In areas with scarce vegetation ($<40\%$ cover), additional, minor reductions in phytomass have been shown to cause significant erosion; whereas areas with more extensive plant cover ($>40\%$) experience little change in soil loss under similar conditions (Copeland, 1965; Zöbisch, 1993). Under certain conditions, wind may also become an effective erosional agent, although there are times when heavy grazing can reduce wind erosion from pastures (Troeh et al., 1991), presumably from compaction of the surface.

Of the biological factors that are affected by grazing, the most neglected would appear to be fauna (Thorp, 1949; Nielsen and Hole, 1964; Hole, 1981; Krausman et al., 1985; Mitchell, 1988). Soil fauna (endopedofauna) generally have positive effects on the hydraulic conductivity of soil by (1) increasing the porosity and permeability, (2) improving soil structure, and (3) increasing fertility (see later discussion of forest grazing). The earthworm (*Lumbricina*) comes first to mind, and according to Wallworth (1970), overshadows all other fauna in its effects on soil, most of which are beneficial (Hole, 1981), but there are instances where the effects can be negative (Hole, 1981). Although the literature is very sketchy, it appears that fauna ranging from earthworms to moles have more difficulty surviving in the impacted soil condition resulting from heavy grazing (Hole, 1981; Abbott et al., 1979). Cluzeau et al. (1992) found that 90% of the earthworms and cocoons were located within 10 cm of the surface and that grazing primarily disturbed those species living near the soil surface. Although the direct effects of grazing (compaction, decrease of vegetation and organic material, etc.) would affect all levels of endopedofauna, reductions of lower forms such as earthworms would have secondary effects on higher forms such as vertebrates. One example observed by Trimble in Tennessee was that over a ten-year period, moles (*Scapanus latimanus*) were ever-present pests in the lawn about a farm residence while they were never observed in the surrounding heavily grazed pasture. All grazing was halted in 1990 and by 1995, moles became widespread in the former pastures, and kept a substantial proportion of the ground disturbed (Fig. 5).

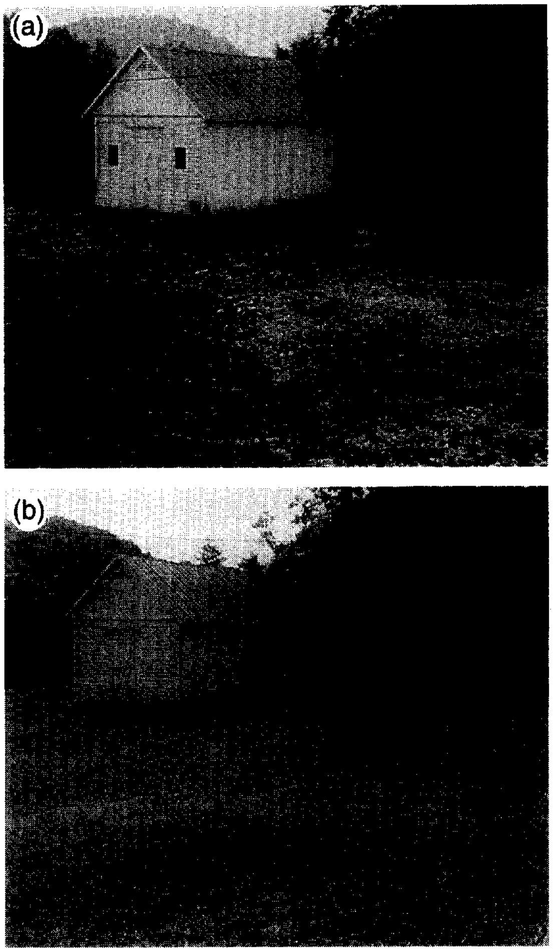

Fig. 5. Recovery of grassland after cessation of grazing in 1989. (a) 1989, (b) 1994, grass kept mowed. Visible rocks of farm road in foreground now mostly buried, perhaps by biopedoturbation. Moles are now active over much of the area. Giles County, Tennessee.

2.3. *Infiltration*

The hydrologic effects of grazed and compacted rangelands in the western United States were often the objects of government-sponsored experimental watershed research in the 1930s through the 1960s (e.g. Dunford, 1949, cited in Branson et al., 1981; Lull, 1959; Copeland, 1965; Lusby, 1970). Most of this earlier work on rangelands suggests significant effects from grazing on runoff and sediment yield (Figs. 6 and 7). Lusby (1970), working in western Colorado, found that runoff from a grazed watershed was 30% greater than that from an ungrazed watershed. The latter had previously been grazed (at the same intensity as the grazed watershed), but immediately showed signs of recovery including reduced runoff. Within 3 years, the difference in runoff between the two watersheds was significant. Rauzi and Smith (1973) report that infiltration rates varied with grazing intensity on pastures in northeastern Colorado. Under ''light'' to ''moderate'' grazing, infiltration rates were 5.6 and 5.9 cm h^{-1}, respectively, of which about 30% of the total water infiltrated within the first 15 minutes. Under ''heavy'' grazing, the infiltration rate was 4.8 cm h^{-1}, and 44% of the total water was infiltrated within the first 15 minutes. Usman (1994) also found that infil-

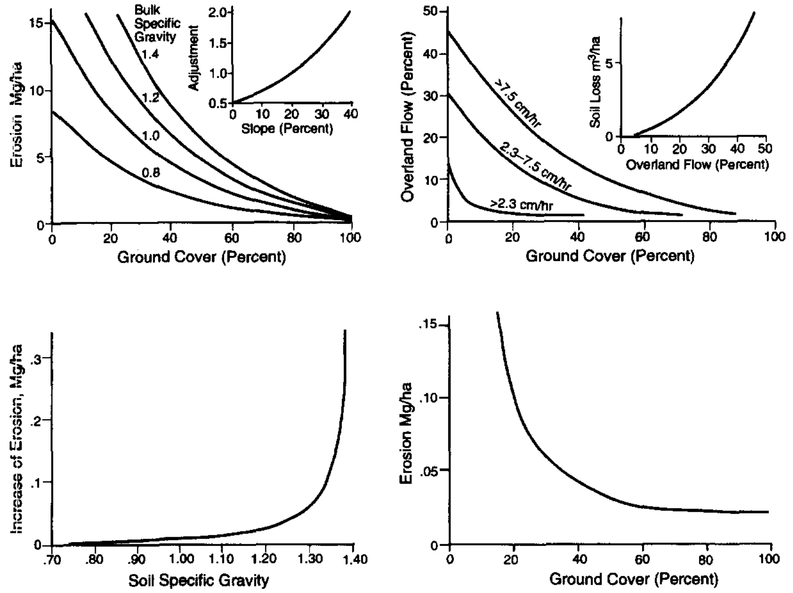

Fig. 6. Some relationships of soil density and ground cover with overland flow and erosion in Utah and Montana. Redrawn from Copeland (1965).

tration rates decreased substantially under "moderate" and "heavy" grazing and he attributed these reductions to changes in soil structure. Gifford and Hawkins (1978) analyzed much of the available published data (Fig. 8) and found the differences in infiltration due to "light" and "moderate" grazing were insignificant. The effects of "heavy" grazing, however, were statistically different. The authors conclude that "moderate/light" grazing reduces infiltration capacity to about 3/4 of the ungrazed condition; "heavy" grazing reduces infiltration capacity to about 2/3 of the "moderate/light" condition or 1/2 of the ungrazed condition (Gifford and Hawkins, 1978, p. 310).

By the 1970s, the USDA had incorporated some of the experimental data into relatively simple runoff models which considered the severity of land use and the normal hydraulic conductivity of the soil (Hydrologic Group A–D) as well as several other physical factors (e.g., USDA-SCS, 1972). To illustrate the effect of grazing on runoff as well as the utility of these runoff models, we ran the model for a 120 ha basin in southeastern Arizona with an average slope of 11.5 percent. Soils have medium to slow permeability and are classified in Hydrologic Groups B and D (USDA-SCS, 1981). Calculations were made for the 25-year, 24-hour storm of 9 cm, and suggest that peak storm runoff from a "heavily" grazed condition would be 2–3 times that from a "lightly" grazed condition. Although this estimate and preceding graphs are not definitive, they do give a comprehensive estimate of the hydrologic effects of grazing on rangelands.

A footnote to the USDA runoff models is that they predict a much greater effect of grazing on less permeable soils (Hydrologic Groups C and D) than on more permeable soils (Groups A and B). Given that grazing affects the upper 25 cm or so, and given that permeability is often a function of soil depth, the deeper soils may be less affected because the thicker unimpacted zone can still conduct water.

Rangeland studies appearing in the past two decades or so appear to suggest a somewhat more ambivalent view of the effect of grazing on runoff. In fact, there are studies which suggest that "light" or even "moderate" grazing may not significantly change, or indeed, may even improve soil infiltration (Rauzi and Smith, 1973; Thurow et al., 1986; Warren et al., 1986b). We have analyzed a large, but incomplete array of published research (Fig. 9). Although runoff and erosion are the important geomorphic variables, we have considered infiltration rather than runoff because (1) there is relatively little comparative literature on runoff as compared to infiltration, and (2) runoff embraces not only land treatment but also climate, primarily water budgets and frequency–magnitude relationships of pre-

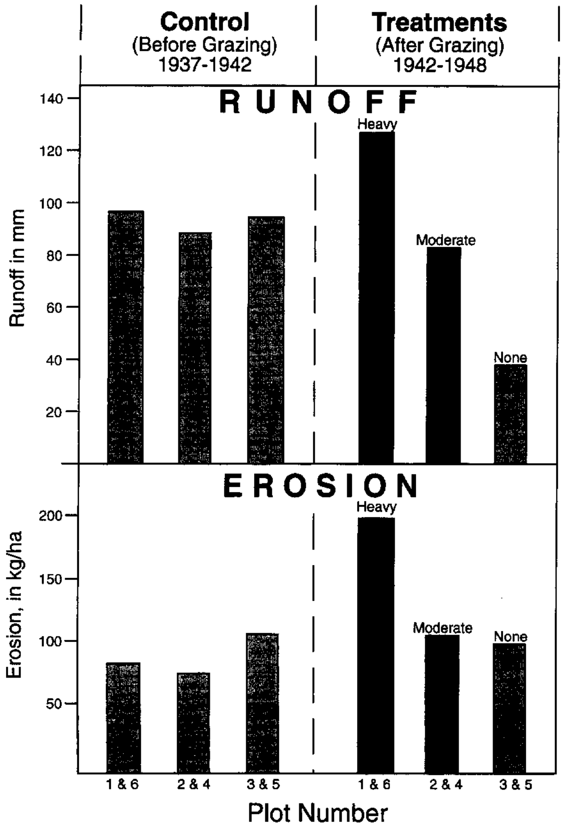

Fig. 7. Runoff and erosion, June–September, for bunchgrass rangeland subjected to different intensities for grazing, near Colorado Springs (Dunford, 1949). Data from Branson et al. (1981).

cipitation and the variables are rarely separated. Erosion rates are even more sketchy and are site or regional specific. Thus, infiltration gives a better base of comparison given the present state of the science.

It will be observed that there is a general decrease of infiltration capacity with grazing intensity, but there is also large variance about all of the means. Log transformation of the infiltration data produced approximately normal distributions for each land use category. A one-way ANOVA of the log-transformed data indicates that there is a statistically significant difference ($\alpha = 0.01$) between the infiltration rates on the four different land uses. Further analysis utilized the Scheffé's test to distinguish significantly different mean infiltration rates between land use categories. A statistically significant difference ($\alpha = 0.01$) in infiltration rates was evident only between ungrazed and "heavily" grazed land. This result is interesting as recent studies have suggested that rangelands are significantly impacted only under conditions of "heavy" grazing, and for years various intensive rotation grazing methods have been promoted to encourage the impact of the animals' hooves in breaking up soil surface crusts (Abdel-Magid et al., 1987; Roundy et al., 1992). These results correspond with the aforementioned rangeland literature, and suggest that the land tolerates significant impacts from "light" and "moderate" grazing, but that a threshold is surpassed with "heavy" grazing.

The variance shown by these studies for ungrazed and all three treatments is somewhat daunting, but we can suggest some reasons:

(1) A systematic variance across all treatments is the hydrologic nature of the soil which would include, among other factors, depth, texture, structure, and limiting horizons. Such variables are reflected in USDA Hydrologic Groups A–D (USDA-SCS, 1972) and are discussed elsewhere. Few studies refer to the USDA hydrologic groups, although Tromble et al. (1974) do provide them. We believe this would assist greatly in cross-study comparison. Some soil types have been shown to be more affected than others by differential land use: Van Haveren (1983) notes that soil moisture, texture and proportion of organic matter influence the amount of compaction a soil will experience due to grazing.

(2) As noted earlier, there is no standard definition of treatments in terms of stocking rates, duration, and seasonality.

(3) Also noted earlier were the strong differences among research methodologies used in these studies. For example, some are on natural watersheds, using natural rainfall while the remainder use various types of portable infiltrometers with sometimes dubious real-

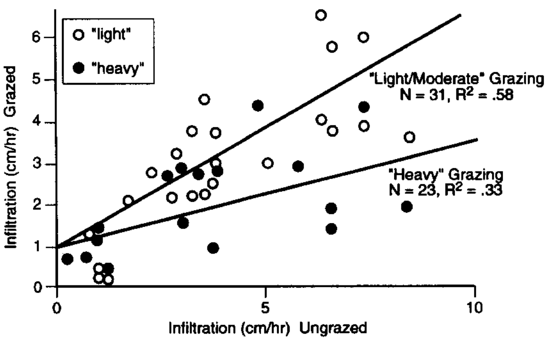

Fig. 8. Impacts of grazing on infiltration, a compendium of western U.S. data. Redrawn from Gifford and Hawkins (1978). See also Lusby (1970).

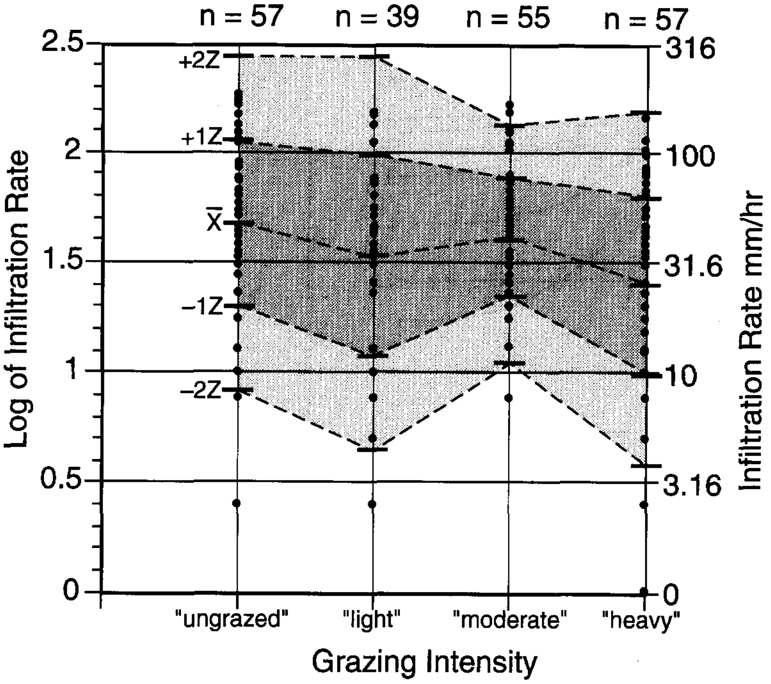

Fig. 9. Relation of infiltration to grazing intensity. Data sources: Gifford and Hawkins (1978), Wood and Blackburn (1981), Thurow et al. (1986), Warren et al. (1986a, b), Weltz and Wood (1986), Abdel-Magid et al. (1987), Heathwaite et al. (1990), Takar et al. (1990), Hofmann and Ries (1991), Mulholland and Fullen (1991), Ferrero (1991), Bari et al. (1993, dry and wet), Usman (1994).

ism. In one case, a simulated 150-year storm was required to produce overland flow. This does not inspire confidence. Moreover, some experiments were not calibrated and/or controlled.

(4) Little consideration is given to prior land treatment and how that might affect the data. There is little knowledge about such lag effects, but they may be significant and persist for decades. Trimble and Lund (1982) and Trimble (1988, 1990) argue that the effects of land abuse and land recovery may take from several years to decades to be manifest. The large data set analyzed by Gifford and Hawkins (1978) suggests that hydrologic impact and recovery of forest may be decadal phenomena but the evidence was not conclusive. Branson et al. (1981) cite several studies which investigate the recovery of soil infiltration rates with the cessation of grazing. Hydrologic recovery was evident within 3 years on pastures in southwestern Wisconsin, within 4 years on sandy loam soils in Utah, within 6 years on ponderosa pine–grassland and within 13 years on grassland locations in Colorado.

(5) There are strong differences of seasonality among the data. Infiltration capacities may be greatly reduced during wet periods.

With reference to points (4) and (5) above, Rostagno (1989) calculated the reduction in infiltration rates on eroded soils in Patagonia, Argentina. Under dry antecedent moisture conditions, infiltration rates were 6.1 cm h^{-1} and 8 cm h^{-1} for uneroded and eroded soils, respectively. At field capacity, infiltration rates were 4.1 cm h^{-1} and 0.6 cm h^{-1} for uneroded and eroded soils, respectively. In contrast, Rostagno (1989) found the difference in runoff and sediment production on grazed and ungrazed soils in Patagonia to be significantly different only during conditions of low antecedent moisture. Under these conditions, runoff was 4% for uneroded soils and 71% for eroded soils. Annual erosion was 292 kg ha^{-1} for uneroded soils and 616 kg ha^{-1} for eroded soils.

Although the data were much more limited, we also examined the short-term changes of infiltration and the effects of land treatment (Fig. 10). Again, there is much variance, but the effects of grazing are similar to those shown in the longer-term analysis (the somewhat bi-modal distributions are probably random relicts attributable to the limited number of studies available).

A relatively neglected area of inquiry is the effect of cattle on the hydrology of humid areas. Extant literature

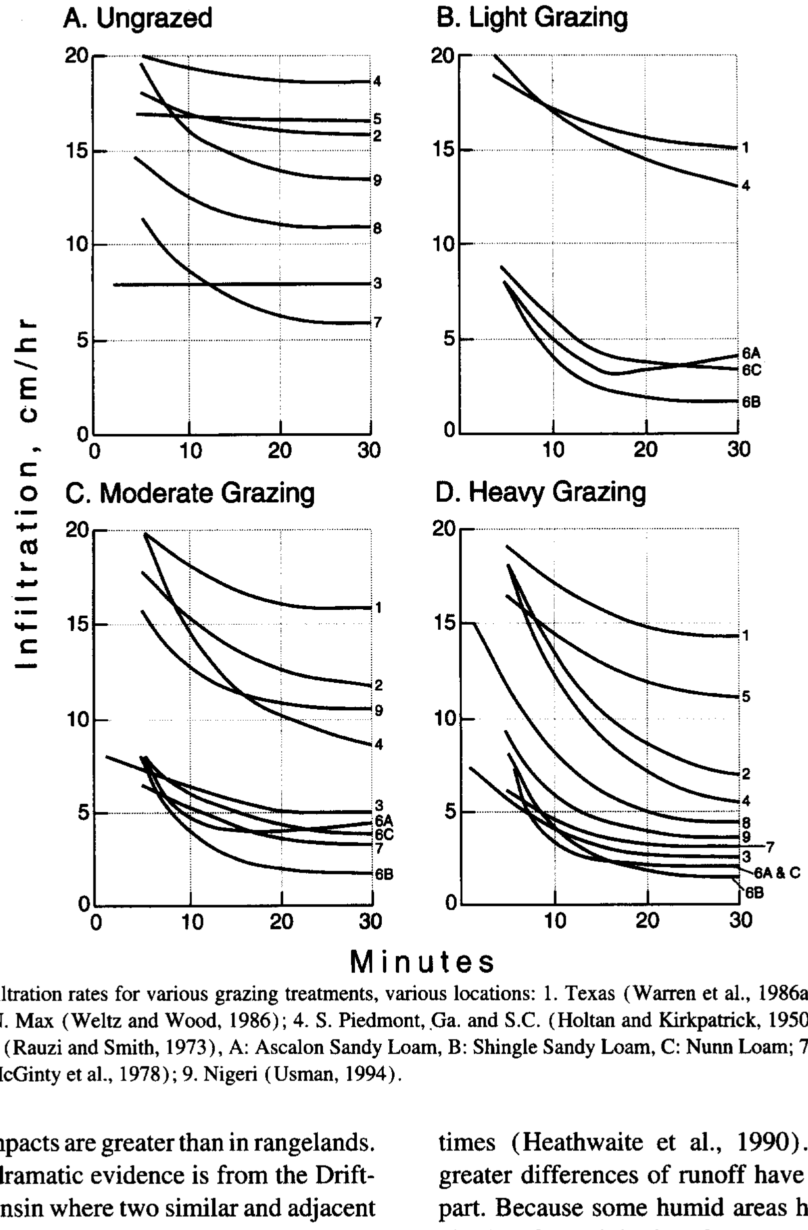

Fig. 10. Short-term infiltration rates for various grazing treatments, various locations: 1. Texas (Warren et al., 1986a); 2. Texas (Wood and Blackburn, 1981); 3. N. Max (Weltz and Wood, 1986); 4. S. Piedmont, Ga. and S.C. (Holtan and Kirkpatrick, 1950); 5. Somalia (Takar et al., 1990); 6. Colorado (Rauzi and Smith, 1973), A: Ascalon Sandy Loam, B: Shingle Sandy Loam, C: Nunn Loam; 7. Louisiana (Linnartz et al., 1966); 8. Texas (McGinty et al., 1978); 9. Nigeri (Usman, 1994).

suggests that the impacts are greater than in rangelands. Perhaps the most dramatic evidence is from the Driftless Area of Wisconsin where two similar and adjacent watersheds (≈ 2.5 ha) had been commonly grazed over a period of years. Cessation of grazing in one basin caused the mean peak flow ratio between the two basins to drop from 0.82 (1963–69) to 0.03 within two years (1970–1972, Sartz and Tolsted, 1974). Measures of bulk density were similar during grazing but within 5 months, the ungrazed side was only 93% that of the grazed side (1.01 g cm^{-3} vs. 1.09 g cm^{-3}). In England (South Devon) "heavy" grazing reduced infiltration capacity by 80% and increased surface runoff by twelve times (Heathwaite et al., 1990). These apparently greater differences of runoff have a climatic basis in part. Because some humid areas have a greater magnitude of precipitation for any given return period (Hershfield, 1961) the excess precipitation over infiltration capacity (Horton concept of runoff) of impacted soils would be greater. This may be seen conceptually by generalizing the 30-minute infiltration graphs in Fig. 10 and comparing them to, for example, the 1-year, 30-minute event rates for various parts of the United States (Hershfield, 1961). Examples are 0.7 cm h^{-1} for E. Wyoming and S. California, 2.0 cm h^{-1} for N. Dakota and New York, and 3.8 cm h^{-1} for E.

Texas and S. Georgia. The comparison suggests that such an event would nowhere cause overland flow on ungrazed land, but ''heavily'' grazed land might produce copious flow especially along the Gulf coast.

Forests are not as hydrologically impacted by grazing as are grassland pastures. For the period 1935–1941 in the Driftless Area of Wisconsin, Hays et al. (1949) found that ungrazed forest produced virtually no runoff while adjacent grazed forest had 3.37% of precipitation leave as runoff. Further work in that region by Sartz (1970) showed that while 4 ungrazed forest catchments had no runoff, an extremely ''heavily-grazed'' forested area had a peak flow of 3.1 mm h^{-1}. For comparison, a ''lightly-grazed'' grass pasture had 8.2 mm h^{-1} and a ''heavily-grazed'' grass pasture had 25.2 mm h^{-1} of runoff. Based in part on this work, Trimble and Lund (1982) offered greatly increasing cattle numbers as a partial explanation for the greatly expanding upland gullies and tributary erosion which occurred early in the 20th century in this region. However, even ''heavily-grazed'' woodlands could not themselves produce enough flow to initiate gullies: woodland gullies were invariably the result of overland flow from upslope agricultural fields and pastures. Nevertheless, ''heavy'' grazing of forest would have made them more vulnerable to erosion (R.S. Sartz, pers. commun., June, 1974).

There is a considerable body of literature which explains well the very high infiltration capacity and hydraulic conductivity of temperate forests (see discussion in Trimble, 1988, pp. 91–103). First, there is the enhancement of infiltration created by the organic duff on the forest floor, the thickness and quality of which is controlled by climate, forest type and age and density of stand. A second factor is the better aggregation of forest soils (Gerrard, 1981; Imeson and Jungerius, 1976). This is due in large part to the presence of the organic duff mentioned above which is incorporated into the soil (Dyrness, 1967). A third factor influencing the high hydraulic conductivity of forest is the pronounced soil porosity including macropores. A major reason for this porosity appears to be the exceptionally high faunal populations (Thorp, 1949; Nielsen and Hole, 1964; Hole, 1981; Krausman et al., 1985; Mitchell, 1988). Macropores have organic origins and are important because they convey non-tension water. According to Sidle et al. (1985, p. 43), ''temperate forests are particularly endowed with micropores because of their organic horizons, extensive rooting systems, and biotic activity''. Of greatest interest here are (a) root routes (especially decomposed roots), (b) routes formed by soil fauna (especially burrows and tunnels), and (c) soil structural routes (Aubertin, 1971; Beven and Germann, 1982; Sidle et al., 1985). The net result of all these factors is that some forest soils have infiltration capacities as high as 500 cm h^{-1} which is about two orders of magnitude higher than pasture and cropland (Sidle et al., 1985). However, subsurface flow through macropores is sometimes turbulent and limited erosion can occur.

As to why cattle grazing has such a limited effect on forest hydrology, one can only speculate, but most forest soils are at least moderately deep so that the nominal 25 cm depth of grazing impact would still leave a thick cross-section of high hydraulic conductivity. There is some evidence that grazing effects in forest, while severe at the surface, do not go as deep as on grassland (Chandler, 1940; Trimble et al., 1951). We speculate that near-surface lateral roots act as a skeletal framework, supporting the soil and partially protecting the upper zone from extreme compaction. Even with a compacted surface, water could enter the soil around stems and surface roots. Another important point mentioned by the reviewers of this paper is the fact that cows spend less time trampling forest soils, simply because there is less forage.

3. Streams, ponds and riparian areas

Cows, unlike sheep, appear to love water and spend an inordinate amount of time together lounging in streams and ponds, especially in summer (Platts, 1991), sometimes going in and coming out several times in the course of a day. In more arid regions, riparian areas may be an important source of food, especially in the drier seasons. Cattle can break banks down directly by trampling and they can create hydraulic roughness which can increase tractive force. They also reduce resistance by removing protective vegetation and loosening soil.

Within semi-arid rangelands, studies indicate that cattle favor riparian areas over uplands. Kauffman and Krueger (1984) found that 81% of the vegetation removed by cattle was from a riparian area — an area covering only 2% of the total grazing space. Clary and

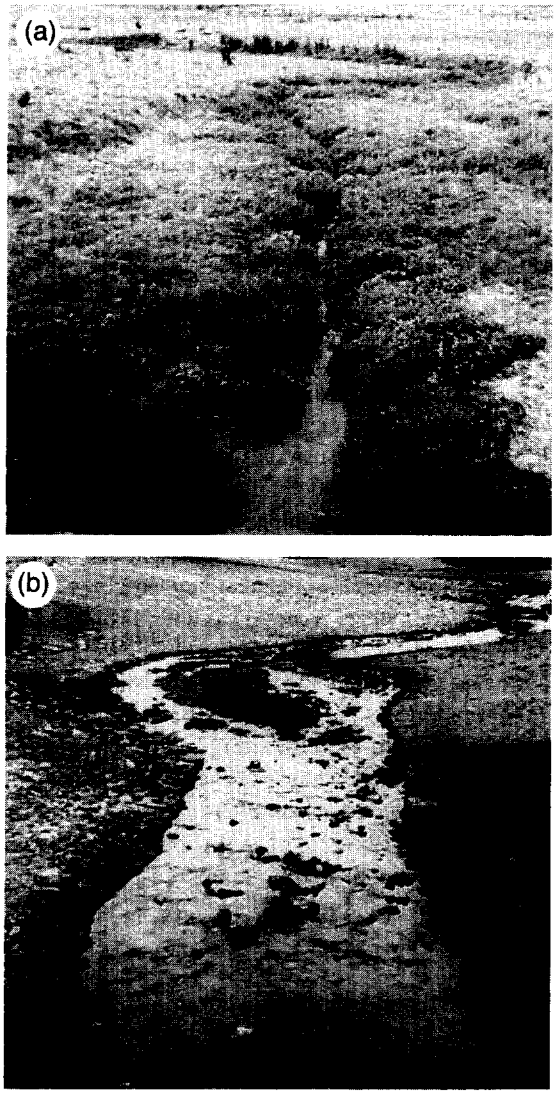

Fig. 11. Two contiguous reaches of tributary with low, silty banks. (a) Light to moderately grazed. (b) Heavily grazed. Iowa County, Wisconsin, 1991. Compare with Figs. 12 and 13.

Webster (1989) report grazing rates 5 to 30 times higher in riparian areas than on uplands, depending on the size of the riparian zone (see also Platts and Nelson, 1985). The authors note that the following features may contribute to greater use of riparian areas by cattle: (1) higher forage volume and relative palatability in the riparian area as opposed to uplands; (2) shorter distance to water; (3) closeness upslope to best upland grazing sites; and (4) microclimatic features. The latter, according to Kauffman and Krueger (1984), might include the availability of shade and thermal cover.

3.1. Force

Overgrazing alters streambank morphology by creating false, setback banks (Kauffman and Krueger, 1984). The most damage appears to occur with ingress and egress from the stream when powerful force from a hoof can actually shear off slices of bank material ≤ 10 cm thick, pushing them toward the stream. Low (< 0.5m), grass-covered, fine-textured banks are particularly vulnerable to trampling by cattle, especially when wet (Clary and Webster, 1990). Because the cows can enter or exit at almost any point, this type of bank may be rather uniformly reduced or removed (Figs. 11–13).

A higher bank or a wooded bank offers the cows fewer locations to enter or leave the stream. Because more force must be applied by scrambling hooves, especially for exits, the banks in these few locations are greatly reduced, creating trough-shaped routes for ingress and egress termed cow ramps (Trimble, 1994). As cow ramps and other morphological irregularities are created by the cows, several positive feedbacks are created at high stream flows. First, the increased hydraulic roughness creates turbulence which accelerates bank erosion when streamflow is bankful or over. The ramps create routes for egress and ingress of water, further eroding the ramps (Fig. 14 and Fig. 15). Finally, the ramps often penetrate the natural levee and allow flow from adjacent slopes to be concentrated, further eroding the ramp.

High cut banks are also vulnerable to grazing. Cows will venture onto extremely steep banks to graze and shearing action is especially pronounced under these conditions, with small chunks of bank either going directly into the stream or being left for the next high flow to entrain. Hydraulic roughness is increased, thus increasing vulnerability during floods. As the cut bank retreats from hydraulic action, floodplain sod is often left draped over part of the bank and might become reestablished on the bank, but trampling often shears this sod away. Finally, our observations suggest that grazing high banks during very wet periods can promote bank slumping. Not only is there the additional mass of cows, but there is occasional deep penetration of hoofs along potential shear planes.

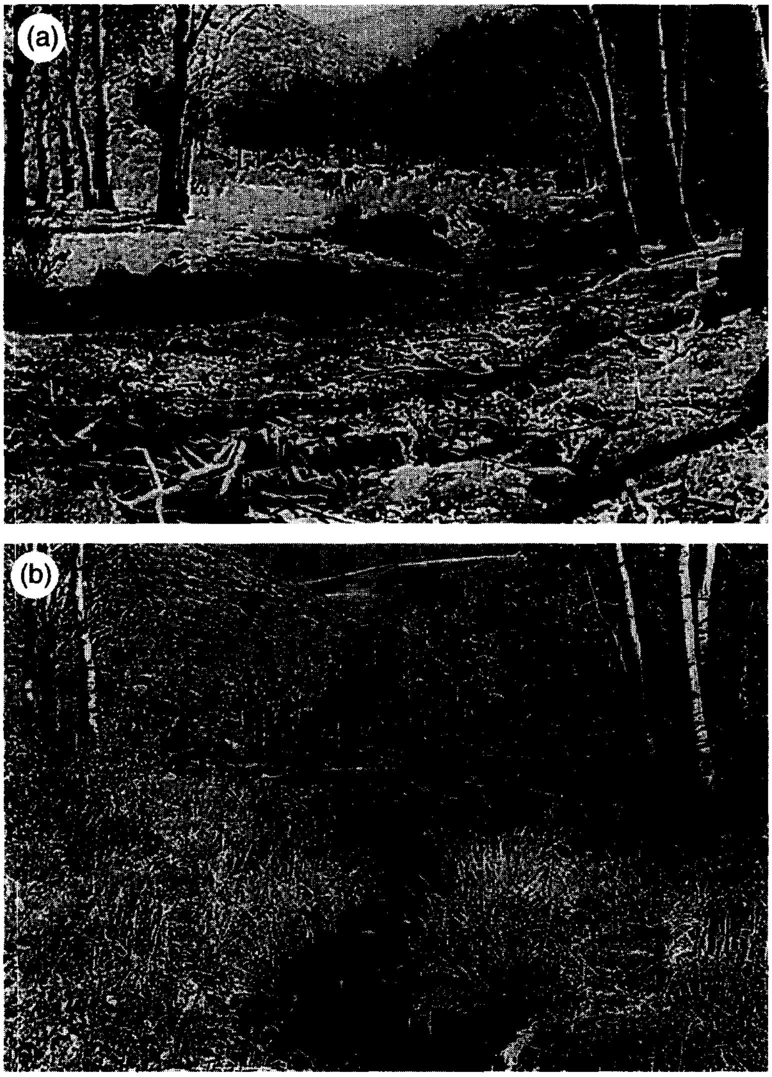

Fig. 12. Restoration of stream with eroded low banks, Mahogany Creek, Nevada. (a) 1975, (b) 1985. From Chaney et al. (1990). Compare with diagram in Fig. 11, and Fig. 13.

3.2. Resistance

Reduced resistance has been implicit in the foregoing discussion of erosional processes on aquatic sites disturbed by cattle. Reduction of resistance has occurred in at least two ways. First there is the trampling which may loosen fragments of soil and make them more erodible. Secondly, there is reduction of vegetation. Grazing of riparian areas can remove up to 80% of riparian vegetation (Platts and Nelson, 1985), thus usually lowering their resistance to erosive flows (Beschta and Platts, 1986). Smith et al. (1993) however, contend that moderate grazing had little effect on the vegetative cover of the streambanks. These authors believe that the vegetation changes with fluctuations in soil moisture rather than grazing. Phytomass per se is not the key — or at least there should be separate phytomass relations for grass and woody vegetation. Grass cover appears to be very effective in anchoring riparian zones (Zimmerman et al., 1967). Reduction of this cover could be expected to increase erosion. On the other hand, the browsing of woody vegetation has uncertain effects. In the short term cattle can greatly reduce the forest understory, but a 6-year study by

Trimble (1994) suggested that removal of understory permitted more light and increased growth of grass. Although floodplains are rarely subjected to enough tractive force to cause erosion, grass cover would probably give more protection than woody vegetation. Indeed it appeared that in some cases, inflexible woody roots and stems actually increased local scour erosion by inducing turbulence. However, young woody shoots, especially of willow (*Salix*), would bend in a flood and provide ground protection. Unfortunately it is precisely this young, tender, flexible growth that cattle prefer.

Wolman (1959) and Hooke (1979) established that wetness of banks was a prime variable in vulnerability to erosion. Not surprisingly, the effects of cattle trampling on streambanks have been found to be significantly correlated with soil moisture content (Marlow and Pogacnik, 1985, 1986; Marlow et al., 1987). These authors found that the greatest amount of bank alteration occurs when soil moisture exceeds 10%, and that reducing the number of cattle in the riparian zone only localizes the damage to the streambanks. A condition hardly mentioned in the literature, other than by Cooke and Reeves (1976), is the formation of trails along floodplains. Although formed by compression and displacement, their form and alignment would conceivably allow them to transport a greater depth and velocity of water during overbank flows so that such trails might be expected to be eroded. Most studies recommend that cattle be excluded from riparian zones until the banks are dry. Thornes (1990) points out that trees, by transpiration, can reduce soil moisture in streambanks during the growing season.

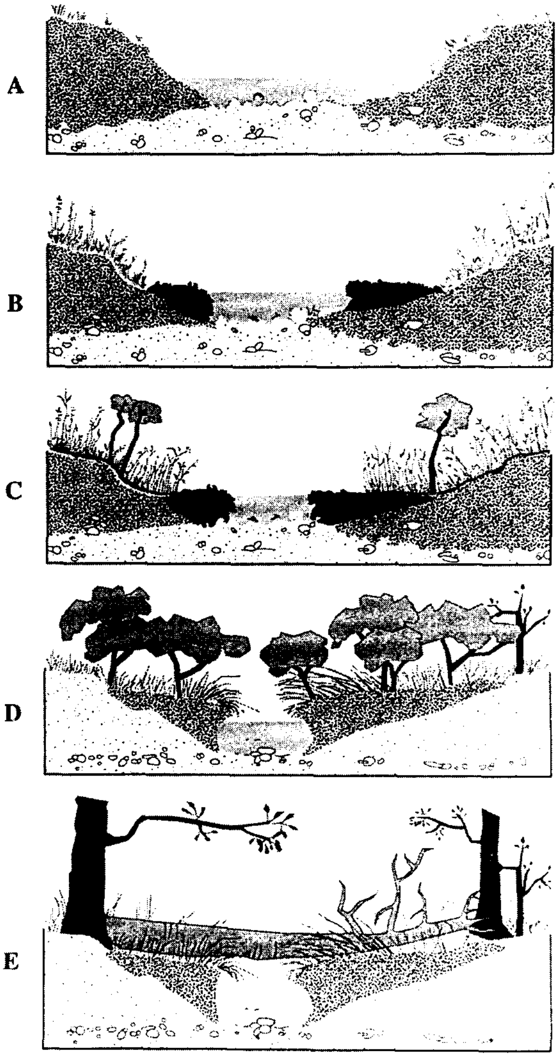

Fig. 13. Schematic, recovery of riparian area, stream with low banks, semi-arid western U.S. Compare with Fig. 11 and Fig. 12. Source: Bureau of Land Management (1994).

3.3. Geomorphic work

The net results of grazing riparian areas, as discussed above, can be both (1) direct modification of stream channels and banks and (2) reduction of resistance to erosion by higher flows which promotes channel erosion. Grazing of riverine and upland areas usually go hand-in-hand so that riverine erosion is increased by the enhanced runoff regime from grazed upland areas discussed in the first part of this paper. Some channels may be especially vulnerable, perhaps because the substrate is very erodible and mobile: trampling in the stream may break up armored layers and expose the substrate. Another vulnerability could be an oversteepened longitudinal profile. When resistance is breached by grazing, it is conceivable that such reaches may erode vertically (degrade) even with no change in streamflow regime. Most usually, there exists the combination of reduced stream channel resistance and increased stream power so that incision may be rapid and spectacular with grave consequences to riparian ecology (Chaney et al., 1990; Platts, 1991; Bureau of Land Management, 1994; Marston, 1994) (Figs. 16 and 17). The perennial arroyo problem of the southwestern United States fits into this category even

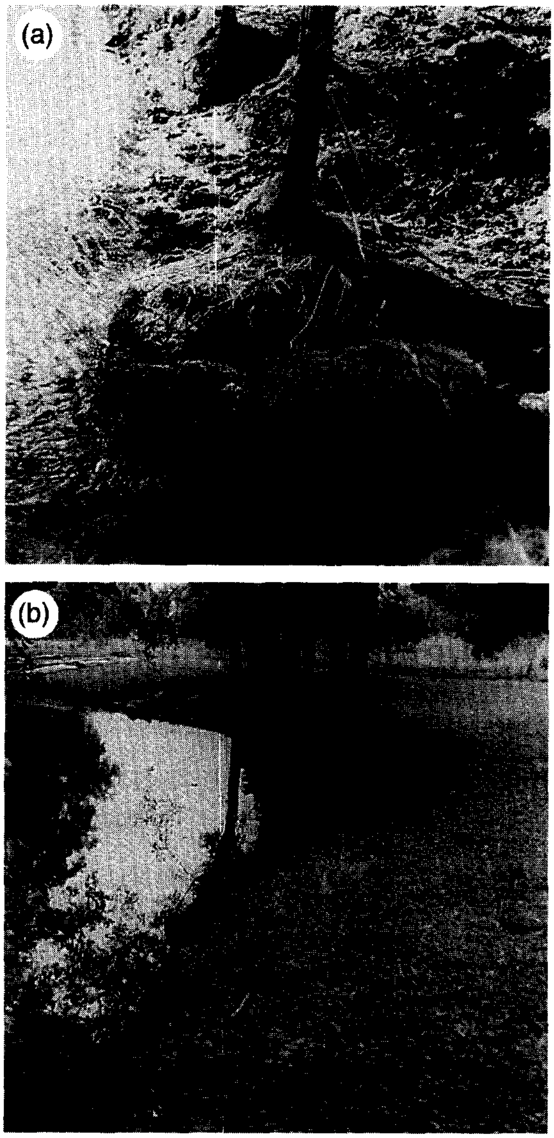

Fig. 14. (a) Cow ramps, Giles County, Tennessee, 1989. Note similarity to lakeshore in Fig. 18. (b) Bank restored to original condition, 1994. See Fig. 15 for effects of ramps on overbank flow.

though it is not yet clear how important the role of grazing is (Cooke and Reeves, 1976; Graf, 1979, 1988).

Shorelines of lakes and ponds are also affected by direct and indirect forces. The direct action of cattle on shorelines is much like that already described for streambanks with bank material being compressed, sheared and pushed toward the water. There are at least two mechanisms which could then transport this material into deeper water. First, slopes adjacent to the lakeshore could furnish runoff which would transport the sediment lakeward. Generally, where lakeshores have been abused by cattle, the adjacent slopes have also been compacted and abused as discussed earlier so that copious overland flow would cascade through the cow ramps into the lake. The second mechanism is wave action which could be important in larger lakes with adequate fetch. Obviously a windy climate would also be important. Lancelot (Capability) Brown, the renowned English 18th century landscape architect, was quite aware of the grazing problem, and sometime specified that the shorelines of his lakes be armored by stone, e.g., Petworth in West Sussex (Hinde, 1987). In other cases, lakeshores were not protected and later grazing brought dire consequences. The lake at Blenheim, Oxfordshire, a creation of Brown, is one case in point (Fig. 18). Such lakeshores were normally graded smooth, but the projection of the points and the higher level of bank remnants (Fig. 18) suggest that the bank has retreated landward and has been eroded downward.

There appear to be conflicting reports on the relationship between riparian grazing and sediment loss from streambanks. Sediment losses from grazed streambanks have been reported to be significantly greater than their ungrazed counterparts (Platts and Nelson, 1985; Elmore and Beschta, 1987; Marlow et al., 1987; Clary and Webster, 1989, 1990; Platts, 1991; Myers and Swanson, 1994; Swanson and Myers, 1994; Trimble, 1994; see review in Kauffman and Krueger, 1984). However, research by Buckhouse et al. (1981) indicated "no significant patterns of accelerated streambank deterioration due to moderate livestock grazing", and similar findings were reported by Smith et al. (1993). While severity of grazing would be one control, it is possible, as Kauffman et al. (1983a) suggest, that the particular characteristics of some riparian areas make them more vulnerable to soil loss under grazing. Clary and Webster (1989) found that the greatest grazing effect on riparian-dependent resources "occurred in channels with medium to fine textures, easily eroded soil materials and channels typically associated with meadow complexes that are attractive to livestock". We suggest that such contrasting reports on the impact of cattle on riparian zones may not be solely a function of soils, vegetation and seasonality, but may also have a regional climatic force component.

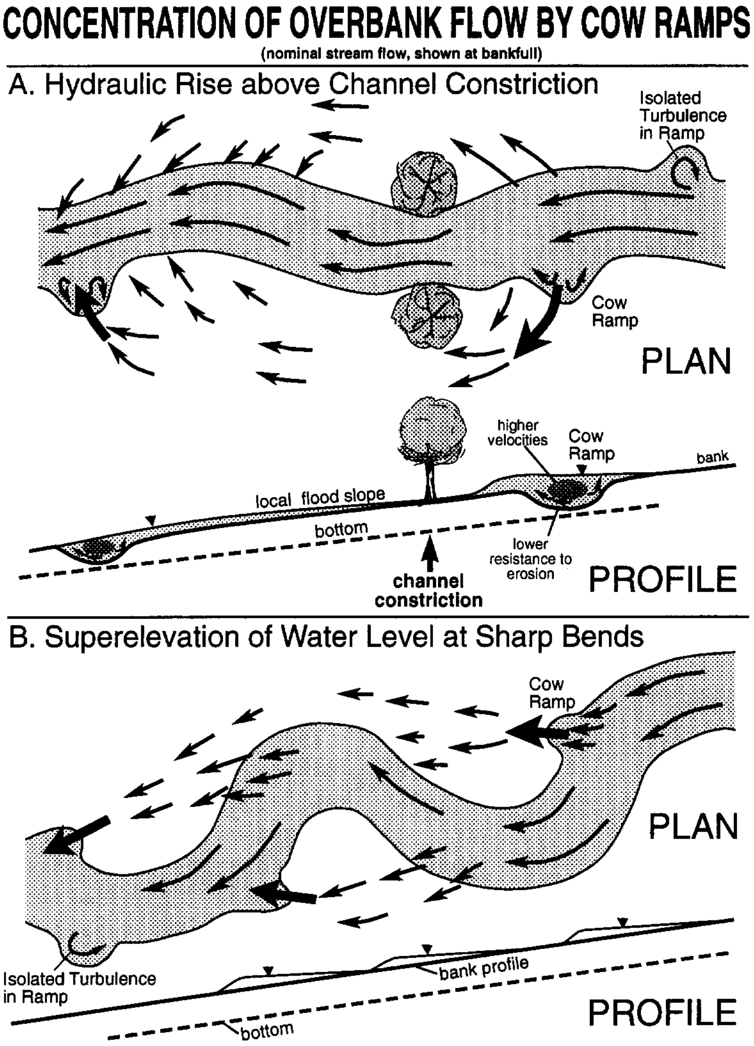

Fig. 15. Idealized diagram to show concentration of overbank flow by cow ramps with consequent scour. Streamflow shown at approximately bankfull. From Trimble (1994).

That is, streams that primarily receive the relatively equitable flow from snowmelt may be less vulnerable than streams which are occasionally subject to high-intensity, long-duration storms with consequently high stream discharges. For example, woody riparian vegetation and large woody debris appear to be almost universally valued as stabilizers of stream channels (e.g., Marston, 1982; Gregory and Gurnell, 1988; see reviews by Kauffman and Krueger, 1984, and Platts, 1991). Yet, this view appears to come largely from observations of streams with relatively equitable flow. While large woody riparian vegetation may decrease the *average* velocity, limited evidence in areas of more extreme flow suggests that large woody vegetation, living or dead, may become a cause of local turbulence and erosion in high flows (Zimmerman et al., 1967; Keller, 1976; Keller and Swanson, 1979; Thorne, 1990; Trimble, 1994; V.R. Baker, pers. commun., Aug. 1989). Much more work is required to fully explore these phenomena. If, however, grass is found to promote more stable stream channels under more extreme hydroclimatological conditions, grazing, perhaps in conjunction with fire, might be a long-range management approach to insure a grass cover. Such hydroclimatological variables could be analyzed, regionalized

Fig. 16. Degrading stream in northern Nevada once lined with willow and aspen and which supported trout. Compare to diagram in Fig. 17. Source: Chaney et al. (1990).

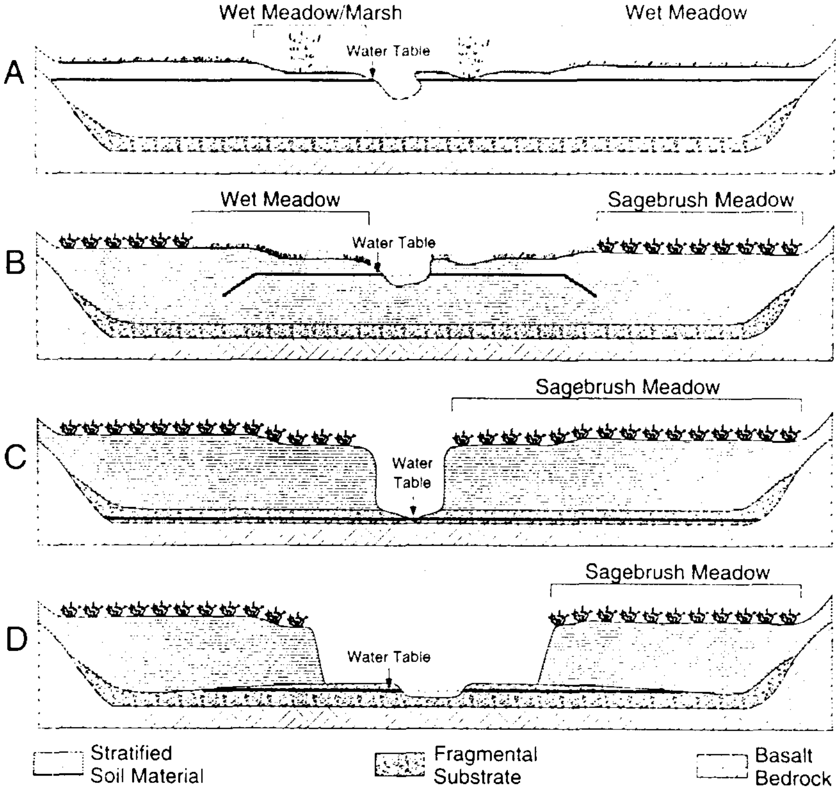

Fig. 17. Schematic of sequential degradation of semi-arid western U.S. stream and destruction of associated riparian environment. Compare to Fig. 16. Source: Bureau of Land Management (1994).

Fig. 18. Cow ramps at Blenheim Lake, Oxfordshire, 1991. Note similarity to cow ramps in Fig. 14. Remnant in foreground and around tree roots in background suggests that bank has been eroded away to a depth of several cm.

and mapped and management could be designed to conform.

4. Conclusions

As we review the voluminous, varied and seemingly often contradictory literature on grazing, it is impossible to avoid a sense of frustration. Of course, there is always a need for more data, but we hope that future investigators will be more careful about framing their studies within the hydroclimatological, edaphic and geomorphological dimensions of the areas being studied. This is especially important in illuminating differences between semi-arid and humid environments where not only may soil development and soil water budgets be different, but storms of highly different sizes and intensities may act on these landscapes. Such studies need to be longer in order to capture more temporal variables including lag effects. Not only would such studies be of greater utility to the regional studies, their transferability would be greater. All of this suggests that hydrologic modeling is necessary to really understand the interaction of variables. Although largely qualitative, the work of Cooke and Reeves (1976) can act as a template with the understanding that we are working towards numerical simulation and even more towards distributive models. The new WEPP model (USDA-ARS, 1994) will hopefully lend itself well to upland processes. Although now imperfect, models of the entire set of hydrologic processes from interfluve to the basin terminus will improve our insights, sharpening especially our specifications for data requirement (e.g. Mendel, 1995). Our call for systems modeling does not detract from empirical site studies in any way. Indeed, we have mentioned many of these lacunae, for example, the effect on endopedofauna of grazing and the resulting effect on hydraulic conductivity of the soil. Among many variables, we need to know more about the values of force and resistance. Reid (1989) for example, showed that a healthy sod could withstand a force of 1000 dyn cm^{-2} whereas bare earth required only 250–500 dyn cm^{-2} for incision (cited in Dietrich et al., 1992). Of course, there are many conditions and much variance about any such number.

We believe the role of cattle and other grazing animals deserves much more attention by geomorphologists. It is surprising that the subject is given limited treatment in such important books as *Geomorphology and Environmental Management* (Cooke and Doornkamp, 1990) and *Land Degradation* (Johnson and Lewis, 1995). We submit this paper with the interest and intent of stimulating more work on the subject.

Acknowledgements

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