Effects of Livestock Grazing on Morphology, Hydrology and Nutrient Retention in Four Riparian/Stream Ecosystems, New Mexico, USA

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Abstract—Land-use practices such as livestock grazing influence the structure and function of riparian/stream ecosystems. In New Mexico, four streams were selected to determine the impact of moderate livestock grazing on morphology, solute transport, and nutrient retention. Each stream contained a reach currently exposed to grazing and an exclosed, ungrazed reach. Channel width/depth ratios and in-stream standing stock of plant biomass were greater in the grazed reaches. Solute transport was determined by injecting a conservative tracer (NaBr) and applying a one-dimensional transport with inflow and storage (OTIS) model. Grazed reaches exhibited enhanced transient storage, represented by a larger cross-sectional area of storage zone relative to wetted channel area (A_s/A). The extent of nutrient retention was determined by co-injecting a reactive tracer ($NaNO_3$) with the conservative tracer. Nitrate uptake lengths were shorter in grazed reaches, an indication of more effective nutrient retention. Our results suggest that moderate livestock grazing alters channel structure and vegetation, influencing ecosystem-level processes.

Riparian/stream ecosystems are three-dimensional interfaces that connect terrestrial and aquatic ecosystems. The riparian component extends laterally to the limits of flooding and vertically to the canopy of streamside vegetation; the aquatic system includes stream surface water and shallow groundwater (Gregory and others 1991, Malanson 1995). Riparian vegetation provides numerous ecosystem functions, including habitat, nutritional resources, and bank stabilization (Crawford and others 1993). Riparian vegetation also has a role as a dispersal site and corridor for biota (Gregory and others 1991). As a whole, riparian/stream ecosystems are valuable resources that contribute to water quality and supply terrestrial and aquatic wildlife habitat and recreational uses.

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Anthropogenic disturbances have greatly altered the structure and functioning of these ecosystems, affecting native communities and influencing biodiversity and successional processes. A disturbance is an episode that disrupts an ecosystem, altering resources, substrate availability, or the physical environment (White 1979). While disturbances can promote diversity, it may be at the expense of existing native communities (Hobbs and Huenneke 1992). Alternatively, many ecosystems rely on disturbances to maintain indigenous communities. Disturbances can thus be viewed as potentially destructive or beneficial. Human-induced disturbances often impart protracted adverse effects to natural ecosystems, such as eutrophication. Processes such as productivity and nutrient cycling respond directly to human modification (Vitousek 1994). For example, Likens and Bormann (1995) found that clearcutting a forest was followed by increased nitrate leaching in its catchment. The loss of nitrogen from the upland system and subsequent loading to the stream could be viewed as a destructive ecological disturbance.

In western North America, riparian/stream ecosystems have been subjected to various anthropogenic disturbances such as livestock grazing, agriculture, mining, industrial and urban intrusion, and river regulation (Crawford and others 1993, Malanson 1995). Livestock grazing is the most extensive land management practice in this region (Fleischner 1994). Previous research has addressed the impacts of grazing on particular components of riparian/stream ecosystems, including vegetation, erosion, geomorphology, water quality, and fish habitat (Moyer 1998 and references therein). However, effects of grazing are less understood from the perspective of the ecosystem as a whole, where nutrients can be regarded as an organizing focus (Krebs 1994). Nutrients regulate rates of important ecological processes, including primary productivity and decomposition (Meyer and others 1988). Stream productivity is dependent on both allochthonous inputs of nutrients and nutrient cycling within the ecosystem (Mulholland and others 1995).

In lotic systems, dissolved nutrients are not cycled in place, but are transported downstream with other solutes. The uptake and release of nutrients by biota in streams is described as nutrient spiraling (Newbold and others 1981). Thus, stream nutrients undergo both hydrologic export and

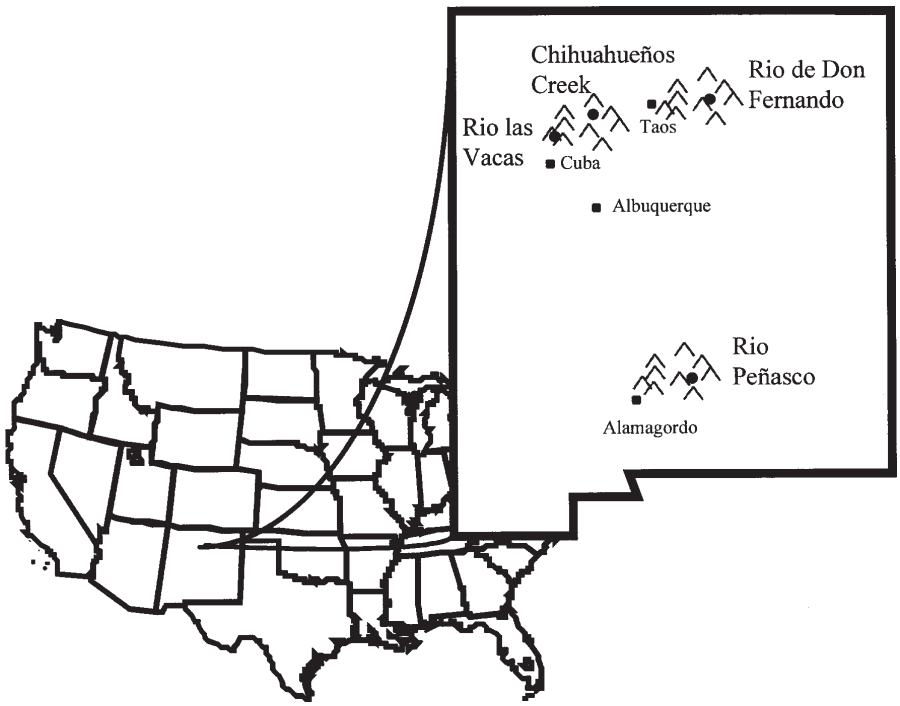

Figure 1—Study site locations, New Mexico, USA.

biological retention (Valett and others 1996). Solutes are also retained hydrologically in flowpaths moving at slower velocities than those predicted by advective transport in the thalweg of a stream (Morrice and others 1997). Hydrologic retention can be determined by the injection of a conservative tracer into the stream. Injection data are incorporated into a transport model that calculates hydrologic parameters such as advection, dispersion, and transient storage (Bencala 1984, Stream Solute Workshop 1990, Runkel and Broshears 1991). Nutrient retention in streams has been measured as nutrient uptake length, the average downstream distance a dissolved nutrient molecule travels before it is utilized by biota (Elwood and others 1983). Nutrient uptake length is inversely related to uptake rate. In a given system, shorter uptake lengths indicate more efficient nutrient cycling.

To maintain ecological functioning and thus support multiple-use status in riparian/stream ecosystems, it is essential to comprehend the movement and retention of solutes, particularly nutrients (Newbold and others 1981, Stream Solutes Workshop 1990). Our research studies the effects of livestock grazing on riparian/stream ecosystem structure and function by examining solute dynamics. In particular, we investigate the influence of moderate livestock grazing on channel morphology, solute transport, and nutrient retention.

Study Sites

Four streams in the Rio Grande catchment of New Mexico were used as research sites (fig.1, table 1). The Rio Peñasco (RP) is located in the Lincoln National Forest in the Sacramento Mountains of southern New Mexico. Chihuahueños Creek (CC) and the Rio las Vacas (RLV) are situated in the Santa Fe National Forest in the Jemez Mountains of northern New Mexico. The Rio de Don Fernando (RDF) is located in the Carson National Forest in the Sangre de Cristo Mountains of northern New Mexico. Study sites are described in more detail (catchment size, elevation, lithology, stream sediments, and riparian and upland vegetation) in Moyer (1998).

Each site is comprised of a riparian/stream section subjected to moderate grazing (grazed) and a nearby section exclosed from grazing (ungrazed) by the U.S. Forest Service. The management history of many grazing sites is unknown, and grazing intensities have been qualitatively defined in several ways (Fleischner 1994). Although our sites are defined as moderately grazed by the USFS, grazing intensities are not well known. At RP, approximately 250 head of cattle are moved through a 111 ha allotment (~2.3/ha) each November, while 40 to 50 cows pass through an 81 ha CC allotment (~0.5/ha) during July to October. At RLV, roughly 40 head of cattle graze on a 60 ha allotment (~0.7/ha) from June to October. At RDF, about 15 cows graze on a 20 ha allotment (~0.8/ha) from July to October (Moyer 1998).

Table 1—Description of the four riparian/stream research sites in New Mexico.

Site	Stream order	Reach length (m)	Base flow discharge (L/s)	Exclosure age (yrs)
Rio Peñasco	1	120	5	6
Chihauhueños Creek	1	200	18	5
Rio las Vacas	3	400	70	12
Rio de Don Fernando	1	120	5	9

Methods

Field work was carried out from June to August 1997. At each site, paired reaches (grazed, ungrazed) were established. Reach lengths were based on stream discharge (table 1, Moyer 1998). Along each reach, five sampling transects were situated at equal intervals, oriented perpendicular to the longitudinal axis of the stream (Moyer and others 1998). Morphologic, hydrologic and nutrient transport features were examined at each site.

Morphology

Wetted width and average depth of the stream were measured at each transect (Rosgen 1994). Values were used to determine the mean width to depth ratio (w/d) for each study reach. We also measured wetted perimeters and calculated ratios of wetted perimeter to wetted width. Stream beds consisted of patch types dominated by bare (unvegetated) sediments, macrophytes, sedges, and filamentous algae (Moyer 1998). The percent of stream area occupied by each patch type was assessed. Total standing stock of aboveground vegetative biomass was calculated using ash-free dry mass concentrations (Benfield 1996) from stream samples and the area of the channel covered by the respective patch types. The percent of riparian area covered by herbaceous and woody vegetation was measured using 1 m^2 quadrats. Several additional measurements were made, including channel gradient and sinuosity, dominant sediment type, porosity, total suspended sediments, and subsurface biomass. These are described in Moyer (1998).

Hydrology

In lotic ecosystems, the transport and retention of solutes are determined by hydrologic factors, i.e., solutes flow with the water. Retention occurs when water moves into slower moving zones relative to the main body of water, where it can be considered temporarily stored (Bencala and Walters 1983, Webster and Ehrman 1996). Transient storage zones include shallow groundwater and surface water environments such as pools and backwaters (Moyer and others 1998, Webster and Ehrman 1996). When a solute pulse is transported downstream, some of the solute mass passes into transient storage zones, temporarily decreasing the concentration in the active channel (Runkel and Broshears 1991). Hydrologic parameters were investigated by employing a conservative (nonreactive) solute to act as a tracer with which to formulate data and construct a solute response curve. A concentrated solution of sodium bromide (NaBr) was injected upstream at a constant rate, elevating the stream Br^- concentration slightly above background levels. At the downstream end of the reach, Br^- concentration was monitored using an Orion 290A ion selective electrode. Surface water samples were collected (1) as the pulse arrived (the rising limb of the solute response curve), (2) once it reached and maintained a plateau concentration, and (3) after the injection was terminated and stream Br^- concentrations approached background levels (during the falling limb of the curve). Samples were analyzed in the lab for Br^- using a Dionex DX-100 Ion Chromatograph. Solute injections are described in more detail in Moyer (1998).

Data from the injections (Br^- concentration vs. time) were plotted as a solute response curve and fit to a hydrologic model of one-dimensional transport with inflow and storage (OTIS; Runkel and Broshears 1991). This model computes values for five hydrologic variables: advective velocity (bulk fluid motion), dispersion (solute spreading), lateral inflow (inputs of unlabeled water), transient storage (temporary storage of solutes in slow-moving compartments), and the storage zone exchange coefficient (rate of exchange between the storage zone and the channel flow) (Runkel and Broshears 1991). Stream discharge, determined by separate injections at the top and bottom of each reach, is entered into the model. Assuming a steady state discharge for the entire reach, a best-fit line through the Br^- response curve is iteratively adjusted by manipulating the following parameters: stream cross-sectional area (A, m^2), dispersion coefficient (m^2/s), storage zone cross-sectional area (A_s, m^2), and the storage zone exchange coefficient (s^{-1}) (Bencala and Walters 1983, Stream Solute Workshop 1990, Moyer 1998). Several hydrologic characteristics were derived based on these parameters, including the area of the storage zone relative to the cross-sectional area of the stream channel (A_s/A, for example Bencala and others 1993). We also determined the hydraulic retention factor (R_h), which describes the amount of time a parcel of water spends in the storage zone per meter of stream ($R_h = A_s$/stream discharge, Morrice and others 1997).

Nutrient Retention

Nutrient retention was measured by the nutrient uptake length. A reactive tracer, nitrate (as $NaNO_3$), was co-injected with the NaBr solution. A reactive solute reacts biotically and/or abiotically in the ecosystem, whereby its concentration is subject to change as it is transported downstream (Stream Solute Workshop 1990, Webster and Ehrman 1996). Once the injected Br^- reached plateau concentration, samples were collected at each transect and analyzed for NO_3-N concentrations via colorimetric methods (Wood and others 1967) on a Technicon AutoAnalyzer II. NO_3-N values were corrected for dilution and background concentration, natural log transformed, and regressed against distance downstream. Nutrient uptake length was calculated as the negative inverse of the relationship between these two parameters (Newbold and others 1981, Webster and Ehrman 1996, Moyer 1998). Nitrate retention methods are discussed in greater detail in Moyer (1998).

In addition to the injections, surface waters were sampled for background levels of biogeochemically active solutes, including NO_3-N, ammonium (NH_4-N), and soluble reactive phosphorus. These data, along with N:P ratios, are presented in Moyer (1998) and Moyer and others (1998).

Statistical Analyses

Statistical analyses were performed to uncover significant differences for a given variable between grazed and ungrazed reaches, both within and across study sites. Nonparametric t-tests were used to identify differences between each reach for each variable. Pearson Correlation Analyses were used to reveal relationships between the different variables. Step-wise multiple linear regressions were used to create predictive models for key morphological, hydrological, and nutrient retention parameters. Additional information pertaining to the statistical analysis of this research is presented in Moyer (1998).

Results

Morphology

Mean w/d ratios were lower in ungrazed reaches at all 4 sites, with significant differences at CC and RLV (P = 0.012 and 0.022, respectively, fig. 2). Wetted perimeter to wetted width (wp/ww) ratios were 1.5, 1.8, and 1.1 times lower in grazed reaches at RP, CC and RLV, respectively. At RDF, the wp/ww ratio was greater in the grazed reach. Aboveground organic matter was greater in the grazed reaches at RP, RLV, and RDF (fig. 3). Significant differences occurred between grazed and ungrazed reaches at RP and RLV (n = 3, P = 0.0018 and n = 3, P = 0.039, respectively). A step-wise multiple linear regression indicated that within each reach, aboveground organic matter was best predicted by w/d ratio (R^2 = 0.95, P = 0.0001). Riparian vegetation was generally more extensive along ungrazed reaches. Ungrazed reaches contained greater areas of either herbaceous or woody riparian vegetation at all sites (table 2).

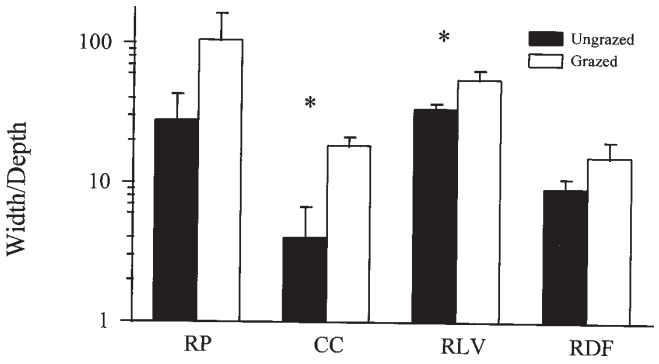

Figure 2—Comparison of wetted width to wetted depth ratios for ungrazed and grazed reaches of Rio Peñasco (RP), Chihuahueños Creek (CC), Rio las Vacas (RLV), and Rio de Don Fernando (RDF). Error bars are standard errors of the mean. Asterisk denotes significance at p < 0.05.

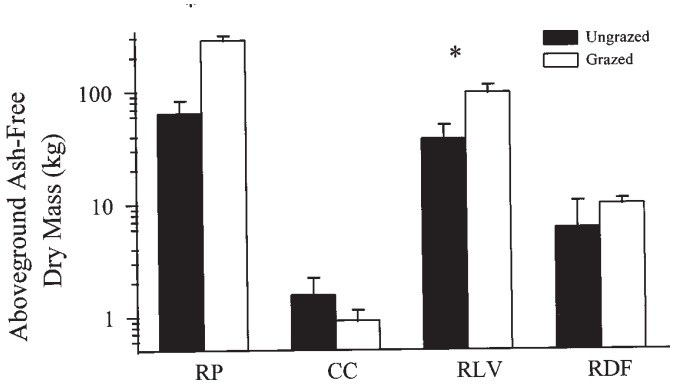

Figure 3—Comparison of total aboveground ash-free dry mass (plotted on logarithmic scale) within ungrazed and grazed reaches of Rio Peñasco (RP), Chihuahueños Creek (CC), Rio las Vacas (RLV), and Rio de Don Fernando (RDF). Error bars are standard errors of the mean. Asterisk denotes significance at p < 0.05.

Table 2—Percent cover by riparian patch-types from grazed (G) and ungrazed (U) reaches at the four research sites. Data are means ± standard errors.

Site	Percent bare soil	Percent herbaceous cover	Percent woody cover
Rio Peñasco-G	28.8 ± 5.5	71.2 ± 5.5	0.0
Rio Peñasco-U	5.9 ± 4.0	94.1 ± 4.0	0.0
Chihauhueños Creek-G	49.2 ± 6.6	50.8 ± 6.5	0.0
Chihauhueños Creek-U	13.4 ± 4.3	86.6 ± 4.3	0.0
Rio las Vacas-G	46.8 ± 11.2	53.2 ± 11.2	0.0
Rio las Vacas-U	49.1 ± 8.3	47.1 ± 9.8	2.5 ± 1.5
Rio de Don Fernando-G	27.5 ± 9.1	70.6 ± 9.3	1.9 ± 1.9
Rio de Don Fernando-U	43.9 ± 9.7	49.4 ± 10.0	6.7 ± 2.3

Hydrology

The average area of the storage zone relative to the cross-sectional area of the channel (A_s/A) was 45 percent smaller in ungrazed reaches across all sites (fig. 4). A step-wise multiple linear regression indicated that within each reach, total aboveground organic matter was an important predictor of transient storage (as A_s/A, R^2 = 0.94, P = 0.0001). Hydrologic retention varied between grazed and ungrazed reaches. Hydraulic retention factors (R_h, s/m) were 5.6, 1.3, and 1.4 times greater in grazed reaches at RP, CC, and RLV, respectively. At RDF, R_h in the ungrazed reach was twice the value found in the grazed reach. Based on cross-site comparisons of R_h, grazed reaches demonstrated on average 303 percent more hydraulic retention than ungrazed reaches.

Nutrient Retention

Grazed reaches generally exhibited more efficient nutrient retention compared to ungrazed reaches. Nitrate uptake lengths were shorter in all 4 grazed sites, with significant differences at RP and RDF (P = 0.0001 and 0.0068, respectively, fig. 5, Moyer 1998). A step-wise multiple linear regression indicated that the area of stream channel devoid

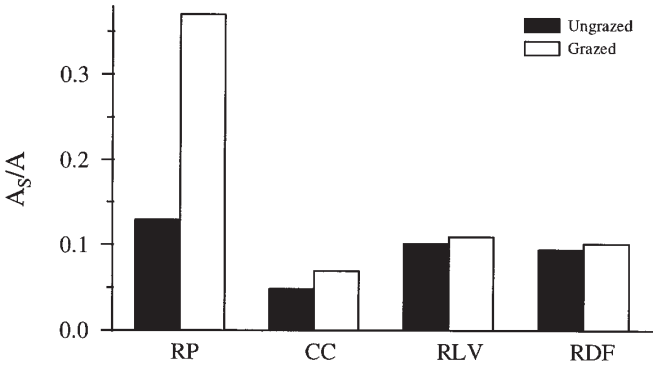

Figure 4—Comparison of area of the storage zone normalized to stream area (A_s/A) for ungrazed and grazed reaches of Rio Peñasco (RP), Chihuahueños Creek (CC), Rio las Vacas (RLV), and Rio de Don Fernando (RDF).

of aboveground vegetation (bare patch-type) was the single most important variable for predicting NO_3-N uptake length ($R^2 = 0.97$, P = 0.0001, fig. 6). Complete, extensive morphological, hydrological and nutrient transport experimental data and analyses resulting from this research are presented in Moyer (1998) and Moyer and others (1998).

Discussion

Grazed stream channels exhibited mean w/d ratios 150 to 500 percent greater than those in ungrazed reaches (fig. 2). Wider, shallower channels are typical of streams exposed to livestock grazing (Duff 1979, Fleischner 1994). Ratios of wetted perimeter to wetted width indicate less channel complexity in grazed reaches, likely diminishing aquatic habitat variability. Herbaceous and woody riparian vegetation covered a less extensive area along grazed reaches. However, in-stream vegetation (sedges, filamentous algae) was more abundant in grazed compared to ungrazed channels, which were characterized by extensive bare patch-types (Moyer 1998). Channel width exerts a positive influence on the amount of in-stream organic matter. Trampling and loss of riparian vegetation increase w/d ratios and create less stable stream banks (Moyer and others 1998). As a result, in-stream vegetation becomes more abundant, composed mostly of vascular hydrophytes (for example sedges, Moyer 1998). Plants of this type are known to colonize disturbed streams, and are typically succeeded by riparian vegetation such as willows and cottonwoods, which help fortify channel structure (Hendrickson and Minkley 1984, Moyer 1998). Our grazed study reaches appear to be maintained in a state of early secondary succession (Moyer 1998) due to the seasonal disturbance imposed by grazing.

Stream hydrologic retention was also influenced by grazing. Conservative tracer injections demonstrated a greater capacity for transient storage in grazed reaches (fig. 4). Transient storage (as A_s/A) was best predicted by the amount of in-stream vegetation. Mulholland and others (1994) also report a positive relationship between A_s/A and in-stream organic matter (as periphyton biomass). Wetted channel width was also an important influence on solute retention

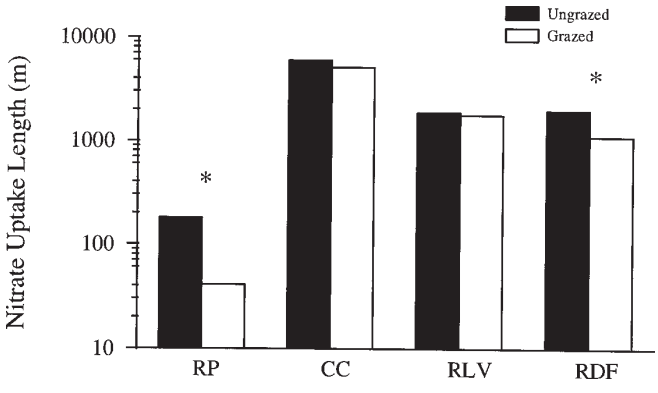

Figure 5—Comparison of nitrate uptake length for ungrazed and grazed reaches of Rio Peñ asco (RP), Chihuahueñ os Creek (CC), Rio las Vacas (RLV), and Rio de Don Fernando (RDF). Asterisk denotes significance at $p < 0.05$.

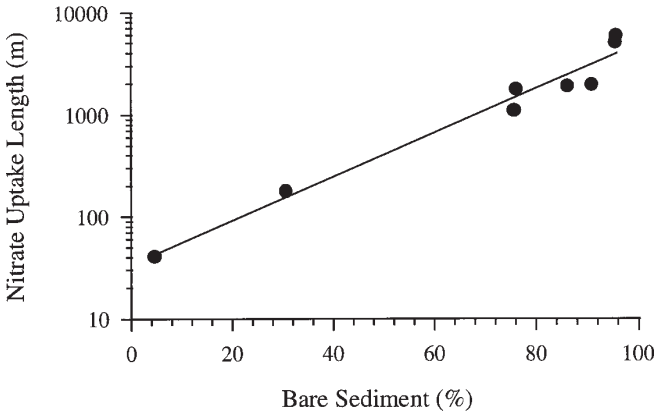

Figure 6—Relationship between nitrate uptake length (plotted on a logarithmic scale) and percent bare sediment. Data are from ungrazed (n = 4) and grazed (n = 4) reaches.

(data presented in Moyer 1998). These findings suggest that channel structure and in-stream vegetation exert strong, retentive influences on the movement of water through the ecosystem.

Nutrients are taken up more rapidly by the biotic community in grazed reaches, indicated by shorter uptake lengths (fig. 5). Uptake lengths are well correlated with the area of stream bed represented by bare patch types (fig. 6). The results suggest that nutrient uptake length is influenced by the amount of in-stream vegetation. Taken together, in-stream vegetation and the hydraulic retention factor (R_h) account for 99 percent of the variability associated with nutrient uptake (Moyer 1998). Hydrologically, it appears the two factors combine to slow the movement of water, allowing the stream community a greater opportunity to utilize the passing nutrients (Moyer and others 1998). Uptake length is inversely related to stream width, and should decrease as a channel widens (Stream Solute Workshop 1990). A significant, positive correlation exists between aboveground organic matter and w/d. The higher w/d values in grazed reaches may contribute to enhanced nutrient retention by promoting the growth of in-stream vegetation and by the increased sediment area with which solutes can come in contact. The successional state of in-stream biota also affects the potential for solute uptake (Grimm 1987). Nutrients were retained more efficiently in the early secondary successional stage typical of grazed reaches. Efficient nutrient retention also is typical during rapid regrowth of disturbed forest ecosystems (Vitousek and Reiners 1975). As succession proceeds, retention efficiency generally declines (Vitousek and Reiners 1975).

Long-term monitoring of riparian/stream ecosystems following the attenuation or elimination of livestock grazing would enable researchers to consider the effects on succession with more accuracy. Studies could occur on a seasonal basis to include active and dormant grazing intervals, as well as the effect of higher stream discharges (for example during spring runoff). Additionally, a more quantitative, precise definition of grazing intensity would be useful. The effects of moderate grazing versus overgrazing could be compared, enabling researchers to provide land managers with more accurate information (for example the expected effects of a particular grazing regime on a riparian/stream ecosystem).

Conclusions

With respect to ungrazed riparian/stream ecosystems, stream channels are wider and less complex in moderately grazed systems. In addition, in-stream vegetation is more abundant in grazed streams. As a result, nutrients are retained to a greater degree compared to ungrazed sites characterized by less in-stream vegetation and more established riparian vegetation. The effects of grazing on ecosystem-level processes in streams have not been well studied. At the present time we know of no analogous study with which to compare our research. It is uncertain how alterations to hydrology and nutrient retention affect the ecosystem within and downstream of grazed areas. A knowledge of nutrient cycling is an important component in the management of ecosystems, particularly in lands mandated for multiple-use. Land-use decisions such as livestock grazing have the potential to modify nutrient dynamics. The impacts of these changes in nutrient dynamics on riparian/stream ecosystems remain to be determined.

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References

Bencala, K.E. 1984. Interactions of solutes and stream bed sediments 2. A dynamic analysis of coupled hydraulic and chemical processes that determine solute transport. Water Resources Research. 20: 1804-1814.

Bencala, K.E.; Duff, J.H.; Harvey, J.W.; Jackman, A.P.; Triska, F.J. 1993. Modelling within the stream-catchment continuum. In: A.J. Jackman, M.B. Beck, and M.J. McAleer, eds. Modelling change in environment systems. John Wiley and Sons, New York.

Bencala, K.E.; Walters, R.A. 1983. Simulation of solute transport in a mountain pool-and-riffle stream: a transient storage model. Water Resources Research. 19: 718-724.

Benfield, E.F. 1996. Leaf breakdown in stream ecosystems. In: F.R. Hauer and G.A. Lamberti, eds. Methods in stream ecology. Academic Press, San Diego. 579-589 pp.

Crawford, C.S.; Cully, A.C.; Leutheuser, R.; Sifuentes, M.S.; White, L.H.; Wilber, J.P. 1993. Middle Rio Grande ecosystem: bosque biological management plan. U.S Fish and Wildlife Service, District 2, Albuquerque, NM.

Duff, D.A. 1979. Riparian habitat recovery on Big Creek, Rich County, Utah. In: O.B. Cope, ed. Proceedings of the forum-grazing and riparian/stream ecosystems. Trout Unlimited, Denver, CO. 91-92 pp.

Elwood, J.W.; Newbold, J.D.; O'Neill, R.V.; Van Winkle, W. 1983. Resource spiraling: an operational paradigm for analyzing lotic ecosystems. In: T.D. Fontaine III and S.M. Bartell, eds. The dynamics of lotic ecosystems. Ann Arbor Science, Ann Arbor, MI. 3-27 pp.

Fleischner, T.L. 1994. Ecological costs of livestock grazing in western North America. Conservation Biology. 8: 629-644.

Gregory, S.V.; Swanson, F.J.; McKee, W.A.; Cummins, K.W. 1991. An ecosystem perspective of riparian zones. Bioscience. 41: 540-551.

Grimm, N.B. 1987. Nitrogen dynamics during succession in a desert stream. Ecology. 68: 1157-1170.

Hendrickson, D.A.; Minckley, W.L. 1984. Ciengas-vanishing climax communities of the American Southwest. Desert Plants. 6: 130-175.

Hobbs, R.J.; Huenneke, L.F. 1992. Disturbance, diversity, and invasion: implications for conservation. Conservation Biology. 6: 324-337.

Krebs, C.K. 1994. Ecology. Fourth edition. HarperCollins College Publishers, New York.

Likens, G.E.; Bormann, F.H. 1995. Biogeochemistry of a forested ecosystem. Springer-Verlag, New York.

Malanson, G.P. 1995. Riparian landscapes. Cambridge University Press, New York.

Meyer, J.L.; McDowell, W.H.; Bott, T.L.; Elwood, J.W.; Ishizaki, C.; Melack, J.M.; Peckarsky, B.L.; Peterson, B.J.; Rublee, P.A. 1988. Elemental dynamics in streams. Journal of the North American Benthological Society. 7: 410-432.

Morrice, J.A.; Valett, H.M.; Dahm, C.N.; Campana, M.E. 1997. Alluvial characteristics, groundwater-surface water exchange and hydrological retention in headwater streams. Hydrological Processes. 11: 253-267.

Moyer, D.L. 1998. Influence of livestock grazing and geologic setting on morphology, hydrology, and nutrient retention in four southwestern riparian-stream ecosystems. Master's thesis, Department of Biology, University of New Mexico, Albuquerque, NM.

Moyer, D.L.; Dahm, C.N.; Valett, H.M.; Thibault, J.R.; Marshall, M.C. 1998. Effects of livestock grazing on morphology, hydrology, and nutrient retention in four southwestern stream ecosystems. In: D.F. Potts, ed. Proceedings of AWRA Specialty Conference, Rangeland Management and Water Resources. American Water Resources Association, Herndon, VA, TPS-98-1. 397-408 pp.

Mulholland, P.M.; Steinman, A.D.; Marzolf, E.R.; Hart, D.R.; DeAngelis, D.L. 1994. Effect of periphyton biomass on hydraulic characteristics and nutrient cycling in streams. Oecologia. 98: 40-47.

Mulholland, P.M.; Marzolf, E.R.; Hendricks, S.P.; Wilkerson, R.V.; Baybayan, A.K. 1995. Longitudinal patterns of nutrient cycling and periphyton characteristics in streams: a test of upstream-downstream linkage. Journal of the North American Benthological Society. 14: 357-370.

Newbold, J.D.; Elwood, J.W.; O'Neill, R.V.; Van Winkle, W. 1981. Measuring nutrient spiralling in streams. Canadian Journal of Fisheries and Aquatic Sciences. 38: 860-863.

Rosgen, D.L. 1994. A classification of natural rivers. Catena. 22: 169-199.

Runkel, R.L.; Broshears, R.E. 1991. One-dimensional transport with inflow and storage (OTIS): a solute transport model for small streams. CADWES Technical Report 91-01.

Stream Solute Workshop. 1990. Concepts and methods for assessing solute dynamics in stream ecosystems. Journal of the North American Benthological Society. 9: 95-119.

Valett, H.M.; Morrice, J.A.; Dahm, C.N.; Campana, M.E. 1996. Parent lithology, groundwater-surface water exchange and nitrate retention in headwater streams. Limnology and Oceanography. 41: 333-345.

Vitousek, P.M. 1994. Beyond global warming: ecology and global change. Ecology. 75: 1861-1876.

Vitousek, P.M.; Reiners, W.A. 1975. Ecosystem succession and retention: a hypothesis. Bioscience. 25: 376-381.

Webster, J.R.; Ehrman, T.P. 1996. Solute dynamics. In: F.R. Hauer and G.A. Lamberti, eds. Methods in stream ecology. Academic Press, San Diego. 145-160 pp.

White, P.S. 1979. Pattern, process, and natural disturbance in vegetation. The Botanical Review. 45: 229-299.

Wood, E.D.; Armstrong, F.A.; Richards, F.A. 1967. Determination of nitrate in seawater by cadmium-copper reduction to nitrite. Journal of the Marine Biology Association of the United Kingdom. 47: 23-31.