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Livestock Grazing Effects on Phosphorus Cycling in Watersheds

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ABSTRACT

Elevated phosphorus (P) loading of wetlands, streams, lakes, and reservoirs can occur from nonpoint sources such as grazing of uplands, wet meadows, and palustrine wetlands. Erosion caused by livestock grazing or any activity will increase the total P load in streams; however, herbivores can also harvest P from forage and export a significant amount of P from the watershed. Some land managers fail to recognize that the P taken up by plants will continue to cycle through soil and water. Dissolved P or P attached to soil particles suspended in water are the primary vectors of P movement in a watershed. Herbivores add another vector with more opportunities to export P from the watershed. Using best management practices such as rotational grazing, buffer strips next to wetlands, and proper irrigation management should reduce overland flow and streambank erosion. Livestock grazing should harvest and remove a significant amount of P from the ecosystem by incorporation into bone and tissue mass of growing animals and beef export from the basin. The Phosphorus Uptake and Removal from Grazed Ecosystem (PURGE) model uses three separate methods to estimate P retention in cattle, and using limits of the input variables, predicted a range from 4 to 50 Mg P could be removed annually from 17,700 ha of pasture in the Cascade Reservoir watershed in west-central Idaho. With proper grazing management, cattle should be part of a long-term solution to P loading and improvement of water quality in Cascade Reservoir.

Key words: Phosphorus, phosphorus cycling, phosphorus export, livestock grazing effects, model, nutrient

Livestock grazing on public and private lands is increasingly scrutinized for its contribution to nutrient loading of water bodies. While improvements in grazing management usually can reduce nutrient loading, P-loading due to grazing may be overestimated and goals for reduction of nutrient loading may be unrealistic. An understanding of the magnitudes and flows of P within the soil, plant, animal, and microbial pools is essential if land managers are to limit P loading in surface water.

EUTROPHICATION AND NONPOINT SOURCES OF P

The process of water bodies becoming rich in nutrients with the result of abundant microbial growth is called eutrophication. Microbial growth in fresh water systems is often limited by available P. The eutrophication process can remove oxygen from waters, resulting in the death of desirable aquatic species.

Nonpoint sources may contribute 60% of the P load to reservoirs (Valley Soil Conservation District 1991). But often "natural" or background levels prior to grazing or disturbance by man are unknown. Phosphorus load in a stream is a function of geologic materials, soils, topography, vegetative cover, precipitation intensity, and water hydraulics. The contribution of P from natural sources can be difficult to differentiate from anthropogenic sources. Abrams and Jarrell (1995) found that high native P levels and P adsorption characteristics of soils in a tributary watershed of the Willamette River were an important nonpoint source of P. Determining background levels is difficult but critical to setting realistic goals for nutrient loading and its reduction.

NUTRIENT CYCLING

Transport of P by overland flow depends on desorption, dissolution, and extraction of P from soil, and mineralization of plant material and feces. Temperature, precipitation, anaerobic soil conditions, and evapotranspiration rates further influence the process. Plant species composition and rate of decay affect the P leached from plant material. Soil P loss is dependent on the capacity of reactive mineral and organic matter surfaces, pH, and concentrations and interactions of other elements (Broberg and Pearson 1988).

Climate is the overriding variable in nutrient loading. Separating climatic effects from any treatment of the watershed is difficult. Thus, it may be inaccurate to infer trends of P loading without accounting for yearly variation in weather effects and stream flows.

In a system without herbivores, nutrients cycle from soil to soil water, to plants, to litter, and back to soil (Fig. 1). Erosion of soil or leaching through the groundwater transports P to streams and reservoirs. When herbivores are added to the ecosystem, P may be found in more chemical forms with varying solubility. Urine and feces return unabsorbed or unretained P to the soil surface to continue cycling. Also, soluble P from plant leachate can move in overland flow into streams and reservoirs.

RESEARCH DESIGNS

Monitoring studies may be an inappropriate basis from which to infer the effects of grazing management on P loadings. For example, the comparison of one grazed watershed with an ungrazed watershed may have confounded effects with no measure of experimental error. One confounded effect is the watershed itself may be a larger source of variation than treatment; i.e., different soils, aspects, slopes, vegetative cover, etc. In another case, the comparison of P concentration above and below grazed and nongrazed pastures may be confounded by stream and soil differences. Monitoring studies are only useful in recording what happened, not why it happened. Critical studies are needed that test hypotheses of cause and effect in addition to monitoring.

Thus, objectives of this study are to review the literature on P cycling, present the relative masses of P in ecosystem components, describe a simulation model to predict P export in bodies of grazing cattle, discuss best management practices (BMPs) to limit P loading, and propose research to solve nonpoint source P loading.

METHODS

STUDY AREA

This conceptual experiment utilized data from Valley Soil Conservation District (1991) and Division of Environmental Quality (1995) as a case study of the Cascade Watershed in west-central Idaho. The watershed is 1,580 km^2 with elevations from 1,470 to 2,740 m. The mountains surrounding Long Valley are mostly Idaho Batholith except for West Mountain, which is Columbia River Basalt. The valley was formed by a down-dropped fault block which has been filled with glacial debris and alluvial material. Soils have little development.

The average annual precipitation at the city of Cascade is 554 mm and may exceed 1,270 mm at the higher elevations. Most of the precipitation occurs as snow and reaches a maximum depth of 0.3 to 1 m on the valley floor and generally exceeds 2.4 m in the higher mountains during April. The predicted average water available for runoff is 193 mm for a 15-day period (Valley Soil Conservation District 1991). Thus surface runoff would be about 140 mm. Much of the P enters wetlands as a pulse during snow melt. The land use of interest is the 17,800 ha of pastureland, 11% of the watershed.

Eutrophication of Cascade Reservoir is attributed to excess P and other nutrients entering the shallow reservoir through tributaries and irrigation return flows (Entranco Engineers 1991). Estimated sources of P (Division of Environmental Quality 1995) are agriculture (30%), forest (22%), internal recycling (19%), the McCall sewage treatment plant (11%), urban/recreation (8%), rainfall/dryfall (7%), fish hatchery (2%), waterfowl (1%), and onsite wastewater (<1%). Watershed nonpoint sources may contribute 60% of the P load (Valley Soil Conservation District 1991).

MODEL DEVELOPMENT

The Phosphorus Uptake and Removal from Grazed Ecosystems (PURGE) simulation model was developed to estimate P uptake by grass and P retention in bodies of grazing cattle (Shewmaker 1997). Input variables include known, approximate, and assumed values based on measurements, scientific literature, and personal experience. The model does not simulate water flow, soil erosion, or nutrient movement, except by means of ruminant animals. Three methods within the model estimate P exported in cattle tissue.

Method #1 uses net P absorption by animals, daily dry matter (DM) consumption, cattle weight, P concentration in grass, stocking rate, and area grazed as the input variables. These values are multiplied as linear combinations to calculate carrying capacity, total weight gain, grass consumed, P consumed, P retained, and P removed with cattle. Values for net P adsorption are assumed based on Agricultural Research Council (1980) and Miller (1979). The P concentration in grass is assumed to be from 0.18 to 0.30 % reported by Kincaid (1993), Follett and Wilkinson (1995), and data from our lab.

Method #2 uses forage production (Valley Soil Conservation District 1991), P concentration in grass (from Method #1), and the ratio of P removed per plant uptake (Cohen 1980) as input variables. These values are multiplied in linear combinations to calculate P removed by cattle on an area basis and total P removed from the area grazed.

Method #3 was suggested by R.C. Bull, animal scientist at the University of Idaho (personal communication 1996). The P composition of bone and soft tissues in cattle is highly predictable and therefore P export is easily calculated from cattle weight gain while on the pastures. The P content of wet bone tissue is 4.5% (Church 1971), and 80% of total body P is found in the skeleton and teeth. The acreage and weight gains used are those described in Method #1. Based on these assumptions, the values are multiplied to calculate weight gain as bone, bone P, and non-bone P from animal gain. The P in bone growth and non-bone P is added to calculate total P from animal mass gain.

RESULTS

THE SOIL POOL

Soil P is the largest pool by far; however, much of this P is not immediately available. Soils in the Pacific Northwest plus most of Nevada, Utah, and Wyoming generally contain from 0.2 to 0.3 % total phosphate (P_2O_5) in the surface foot of soil (Tisdale et al. 1993). Organic forms of P usually decrease with depth, vary from 15 to 80%, and average 50% of total soil P. If a soil contains 4% organic matter in the surface 15 cm, the organic P content (assuming P is 1% of the organic matter) is (Tisdale et al. 1993):

2.24×10^6 kg soil/ha—15 cm x 0.01 x 0.04 = 896 kg organic P/ha to 15 cm

Soil P may be immobilized to organic forms or chemically fixed inorganic P. Organic P must be mineralized to the inorganic form to be taken up by plants. Inorganic P in solution which is not absorbed by plants or immobilized by microorganisms can be adsorbed to mineral surfaces (labile P) or precipitated as secondary P compounds. Soil pH has a large effect on P fixation or retention. In acid soils, P precipitates as Fe/Al secondary minerals or is strongly sorbed to clay and metal oxide surfaces. In calcareous soils (pH 8), P precipitates as Ca-P secondary minerals or is adsorbed to $CaCO_3$ (Tisdale et al. 1993). Precipitation reactions will occur when the concentration of P and associated cations in the soil solution exceeds the solubility product of the mineral.

Flooding generally increases available P due to conversion of Fe^{3+} phosphates to more soluble Fe^{2+} phosphates and hydrolysis of Al phosphate (Tisdale et al. 1993). Flooding or saturated soil moisture provide anaerobic conditions needed for the microbial population to reduce the Fe^{3+}. This process also generally occurs at pH near neutral.

THE PLANT POOL

The plant pool contains the next largest P source. Phosphorus concentrations in forages may range from 0.14% to over 0.30% P (Follett and Wilkinson 1995). Inorganic P ($H_2PO_4^-$ or HPO_4^{-2}) is taken up by plant roots and most is converted to organic forms upon entry into the root or after it has been transported through the xylem.

What happens to P in plants as plants die or become senescent? Leaves, stems, and roots decompose by weathering and microbial assimilation of nutrients. Nutrients are recycled to the soil by mineralization, where they remain until absorbed by plants or leached from the soil into water bodies. While P losses from live plants are small, 69-80% of total P may be leached from plant residue (Harley et al. 1951; Timmons et al. 1970: c.f. Mays et al. 1980). Much water-soluble P is assimilated by microbial activity and converted back into organic forms. Precipitation intensity and duration, the time between plant dormancy or senescence and the first precipitation, affect the P returned to the soil or lost in runoff (Mays et al. 1980).

THE WATER POOL

Elevated phosphorus (P) loading of wetlands, streams, lakes, and reservoirs can occur from nonpoint sources such as grazed uplands, wet meadows, seasonally flooded, and saturated wetlands. Erosion caused by livestock grazing or any activity will increase total P load in streams.

The Environmental Protection Agency (1989) recommends total P not exceed 0.05 mg/L for a stream at the point where it enters a lake or reservoir, 0.025 mg/L for reservoirs, and 0.10 mg/L for free-flowing rivers. The total P in 1-m depth of reservoir or lake surface water would contain 0.25 kg total P/ha if the concentration was at the Environmental Protection Agency recommended limit. The average total P concentration in Cascade Reservoir ranged from 0.019 to 0.031 mg/L in 1974 (Division of Environmental Quality 1995). Reservoir concentrations ranged from 0.018 to 0.102 mg/L during the period 1978 through 1982 (Zimmer 1983).

Direct rainfall contributed an estimated 0.175 kg P/ha lake surface for water years 1975 and 1981 (Environmental Protection Agency 1977). An assumed value of 0.05 mg P/L multiplied by rainfall volume was used by Division of Environmental Quality (1995) to estimate P content of rainfall when actual measurements are not available. Internal recycling may contribute 19% of the P load in the reservoir (Division of Environmental Quality 1995).

THE ANIMAL POOL

Phosphorus mass in the animal pool will be less than the plant pool (Table 1) if P is not imported as feed supplement. Grazing livestock utilize the forage plant material and recycle most nutrients back into the system. Herbivores add another vector with more opportunities to export P from the watershed (Fig. 1). The net P absorption by cattle is about 90% efficient in young calves and 55% efficient in cows. Bone tissue contains 4 to 4.5% P

Table 1. Hypothetical effects of forage utilization by cattle on recycling of P from plant residue or animal excreta.

Forage Utilization	Soil	Surface Water to 1 m	Plant uptake	Litter return	Animal product	Feces return	Stocking density
%	---	---	---kg P/ha---	---	---		head/ha
0	1875	0.25	15	15.0	0.0	0.0	0.00
25	1875	0.25	15	11.3	0.4	3.4	0.17
50	1875	0.25	15	7.5	1.5	6.0	0.33
75	1875	0.25	15	3.8	3.4	7.9	0.50
100	1875	0.25	15	0.0	6.0	9.0	0.67

Assumptions: The P concentration in the surface 15 cm of soil averages 0.1% P. The bulk density is 1.25 Mg/m3. The surface water to a 1 m depth averages 25 ug/L. Net primary production is 6,000 kg of dry herbage/ha containing 0.25% P. The retention of P in the cattle is 60%. It requires 9,000 kg/ha to be consumed to produce a 400-kg calf containing 2.66 kg of P. Therefore, at a herbage utilization efficiency of 25%, 6 ha will be required; at a utilization efficiency of 75% only 2 ha is required. (After Mays et al. 1980) Fresh bone contains 4.5% P, bone P accounts for 80% of total body P, and bone growth is about 20% of the animal growth (Church 1971).

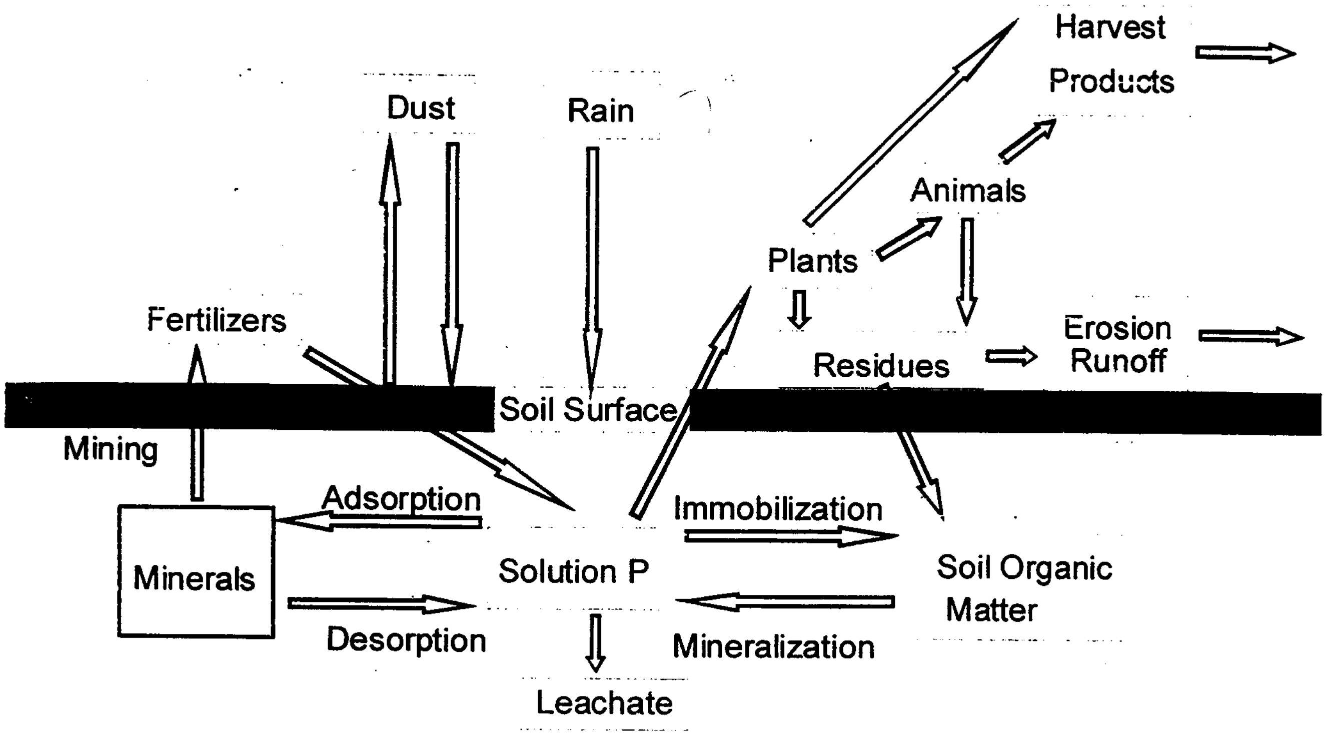

Figure 1. The P cycle on a grazed pasture.

(Church 1971), and from 75 to 80% of total body P is found in the skeleton and teeth. Phosphorus uptake in cattle with daily gains of 0.5, 0.75, and 1 kg/head would be 0.2, 0.88, and 2.16 kg/ha, respectively, during the grazing season (see Method #2, Table 2).

Phosphorus in the diet of grazing animals which is not retained is excreted primarily in the feces. About 0.06 g of organic P is excreted per 100 g of feed eaten (Barrow 1975). Sheep feces retained 40% of the initial total P after 2 years of exposure to weathering and 100 cm of rain (Bromfield & Jones 1970), and 90% of the residual P was in the organic form. Floate (1970a,b,c,d) concluded that organic P in both plant and animal residues appeared to be more of a sink than a source of P cycling.

LIVESTOCK GRAZING EFFECTS ON P CYCLING

A simplistic P budget on grazing land is represented in Table 1. The magnitude of P in plant litter decreases linearly as herbage utilization increases, and the magnitude of P in animal product and dung increases linearly. All of the plant P is recycled unless removed by harvesting

Table 2. Simulations of P export produced by the PURGE model.

1	PURGE4.WB2 Sheet D:	**P Uptake and Removal from Grazed Ecosystems**			
2					
3	**Plant Material on dry matter basis**		**Scenarios**		
4	**Method #1**	**Formula**	1	2	3
5	***Assumptions:***				
6	Net P absorption (%)		80%	70%	60%
7	yearling wt (kg)		250	300	350
8	daily DM consumption (%)		2.50%	2.75%	3.00%
9	P conc. in grass (%)		0.25%	0.28%	0.30%
10	stocking rate (hd-mon/ha)		3	4	5
11	area grazed (ha)		17,668	17,668	17,668
12	rate of gain (kg/hd-day)		0.5	0.75	1
13	***Calculations:***				
14	carrying capacity (hd-mon)	+B10*B11	53,004	70,672	88,340
15	total weight gain (Mg)	+B14*B12*30/1000	795	1,590	2,650
16	grass consumed/hd-day (kg)	+B7*B8	6.25	8.25	10.5
17	P consumed/hd-day (kg)	+B16*B9	0.02	0.023	0.032
18	P retained/hd-day (kg)	+B17*B6	0.01	0.016	0.019
19	**P removed with cattle (Mg)**	+B18*B14*30/1000	19.88	34	50
20					
21	**Method #2**				
22	***Assumptions:***				
23	forage production (kg/ha)		2,000	4,000	6,000
24	P conc. in grass (%)		0.25%	0.28%	0.30%
25	ratio of P removed/plant uptake		0.04	0.08	0.12
26	***Calculations:***				
27	P removed with cattle (kg/ha)	+B23*B24*B25	0.2	0.88	2.16
28	**P removed from watershed (Mg)**	+B11*B27/1000	3.53	16	38
29					
30	**Method #3 (Bull 1995)**				
31	***Assumptions:***				
32	same total weight gain as above		fresh bone = 4.5% P		
33	bone growth is about 20% of the animal growth		bone P = 80% of total body P		
34	***Calculations:***				
35	weight gain as bone (Mg)	+B15*0.2	159	318	530
36	P in bone growth (Mg)	+B35*0.045	7	14	24
37	non-bone P from gain (Mg)	+B36/4	2	4	6
38	**Total P from gain (Mg)**	+B36+B37	9	18	30

hay or by grazing. If P is not supplemented, and grazing animals gain weight and are removed from the watershed, then P is exported in the animal tissue.

The amount of P exported with grazing cattle estimated by the PURGE model is shown in Table 2. Depending on the scenario and method used within the model, the amount of P exported varied from 4 to 50 Mg per 17,700 ha. An average of the moderate values (scenario 2) across the three methods results in 23 Mg P removed from 17,700 ha of pasture lands in the Cascade Watershed annually.

DISCUSSION

THE P CYCLE ON A GRAZED OR HAYED PASTURE

Effects of livestock grazing on nutrient loading are reported with mixed conclusions. Some report that grazing has no measurable impact on N and P pools in soils of infrequently flooded, upland grasslands. Other and sometimes nonscientific papers report that grazing increases P in streams, but these monitoring studies often have inappropriate designs for determining cause and effect. It is clear that any activity accelerating erosion will increase total P load. It isn't clear what effects grazing has on soluble P loading to streams and reservoirs.

Proper grazing management is essential to reducing nutrient loadings to streams. In Oklahoma, Olness et al. (1980) reported that total P concentrations in surface runoff from continuously grazed watersheds ranged from 1 to 1.8 ppm, and were about three times higher than those from rotation-grazed watersheds because of greater soil loss. Average annual losses in runoff from the same rotationally grazed and continuously grazed watersheds were 0.56 and 1.9 kg total P/ha, respectively (Menzel et al. 1978), over a 4-year period. In contrast, Tiedemann et al. (1989) found that differences among grazing strategies for P concentration in streamwater were not significant after the average daily streamflow was used as a covariate in a 5-year study on 13 wildland watersheds in eastern Oregon. In northern Idaho, Jawson et al. (1982) reported annual total P losses in runoff from a grazed watershed over 3 years ranged from 0.1 to 1.3 kg/ha and from 0.1 to 0.17 kg/ha for the ungrazed watershed. However, the watershed effect may be confounded in the study and comparisons are difficult because of differences in topography, vegetative cover, and intensity of precipitation.

There may be a potential for livestock grazing to increase P loading in overland flow situations because the eating and digestion of plant material reduces the particle size in the fecal material containing the undigested P. However, much of the P in the undigested plant material may be in insoluble forms.

Much of the P cycled through animals returns to the surface as dung pats but patterns of dung and urine deposition are not uniform. Such patterns may be more distinct with sheep where from 1 to 2 kg P/ha annually may be transported to ridges where sheep camp at night (Haynes & Williams 1993). Theoretically a BMP of high-intensity and short-duration grazing should provide more uniform dung distribution. However, in a Florida study, soil P redistribution was not different among short-duration, long-duration, and continuous grazing systems on Bermuda grass, but accumulated in the third of the pastures closest to shade and water, probably a result of urine and feces deposition by cattle (Mathews et al. 1993).

Livestock grazing, assuming it is performed with best management practices, in fact removes P from the ecosystem, thereby reducing the extractable soil P. This should produce a greater P sink capacity in the soil because the Fe and Al oxides would still be available to adsorb P from leached plant residue, feces, and urine or from infiltration of water into the soil.

EXPORT OF P

Using moderate values in the PURGE simulation, the model produced an estimate of 23 Mg P removed from the basin, or 1.3 kg P/ha removed. Linqian and Tingcheng (1993) reported that native range in northeastern China dominated by *Leymunes chinenses* could have 1.5 kg P/ha exported annually as hay, which was 21% of the P balance. Wilkinson (1973) calculated that a grazing 500 kg bovine removed 3.3 kg P from the soil into the animal body, while removing 11 Mg of tall fescue hay exported 38 kg P/ha.

Lavado et al. (1996) reported lower soil extractable P in grazed pastures than in pastures excluded from grazing for 13 years on the Pampas in Argentina. Similarly, total P was 4 kg/ha larger in relict than grasslands grazed for 75 years on the Great Plains (Bauer et al. 1987). Diarra et al. (1995) reported 0.15 kg P/ha exported as animal product from the arid Sahel.

Martin and Molloy (1971) estimated the amount of organic P annually contained on a grazed pasture was 269, 6.2, 9, and 3 kg P/ha for a 7.6-cm soil depth, feces, residual herbage, and roots, respectively. They estimated inorganic P annually contained on a grazed pasture was 470, 35, 13, and 4 kg P/ha for a 7.6-cm soil depth, feces, residual herbage, and roots, respectively. The inorganic P in feces seems high in this data and could result from some soil contamination.

RESEARCH AND MANAGEMENT IMPLICATIONS

RECOMMENDATIONS OF BEST MANAGEMENT PRACTICES

Grass buffer strips can be effective in reducing P transport from pastures by increasing infiltration, sedimentation, and decreasing overland flow. Off-stream water development and fencing of riparian areas should reduce (1) streambank degradation, and (2) direct deposit of feces and urine in streams. Rotational grazing systems should provide for a healthier pasture.

Degraded water quality is not beneficial to recreationists, wildlife, homeowners, or agricultural producers. Everyone benefits from using BMPs and other tools—based on science rather than perceptions—to reduce P loading. Recreational and grazing activities that accelerate erosion will increase total P loadings because of P association with soil particles. We should also recognize that properly managed livestock grazing operations will export P from the basin.

RESEARCH NEEDS

The effects of grazing need to be determined by using a design of randomized and replicated treatment areas within the same watershed, and multiple years and watersheds. Volume and nutrient concentration of overland flow and leachate should be measured on these plots as often as every other day during peak snow melt conditions, and as often as twice per week during the grazing season. Overland flow and leachate should be monitored during high, medium, and low runoff years, and total and soluble P concentration should be measured in the soil, forage, and feces in temporal and spatial scales. Cattle gains should be recorded to verify the input variables used in this model. By using a mass balance approach, accounting for most of the P cycling in the ecosystem should be possible. Radioactive isotopes also could be used to trace P cycling in extracted soil cores. Knowing the cycling times and forms should provide insight into adjusting BMPs.

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