Calculating the Cost of Reducing Erosion from a Small Rangeland Watershed

Philip Heilman, Yanxin Duan, Ryan Miller, D. Phillip Guertin

Abstract

Sediment is an important pollutant in the United States. Attempts to control sediment are under consideration for water bodies where sediment-affected water does not support designated uses. To be economically efficient, policies to control sediment should achieve required reductions in sediment at least cost. On rangelands, quantifying the scope of sediment reduction available through land management is problematic given the difficulty in quantifying sediment detachment, transport and deposition processes, and watershed runoff and sediment yield. As many ranches are economically stressed, imposing additional costs to reduce sediment could drive some ranchers out of business. A constrained optimization model was built that simulates the effect of imposing a constraint to reduce watershed sediment yield. The model calculates a rancher's net return subject to technology and soil detachment and sediment yield constraints. By varying the sediment constraints and solving the model multiple times, an abatement cost curve can be estimated. A case study of the Walnut Gulch Experimental Watershed is examined in which the entire watershed is modeled as a single ranch. Results indicate little scope to significantly reduce erosion by reducing herd numbers in the short run. Although additional research is needed to quantify the effects of management on the vegetation community and sediment yields, automated methods to calculate abatement cost curves could improve rangeland water quality decision-making.

Heilman is a Research Biologist at the USDA-ARS, Southwest Watershed Research Center, Tucson, AZ 85719. E-mail: pheilman@tucson.ars.ag.gov. Duan and Miller are graduate students and Guertin is an Associate Professor, School of Renewable Natural Resources, University of Arizona, Tucson, AZ 85721.

Keywords: ranch management, erosion, sediment control, linear programming, Walnut Gulch

Introduction

As part of the Clean Water Act, states are expected to develop Total Maximum Daily Load (TMDL) plans to ensure that water bodies support designated uses. Sediment is a major water pollutant and medium for the transportation of other pollutants that impair water bodies. Development and implementation of TMDL plans is proceeding within each state.

In the west, TMDLs to address sediment are complicated by the great uncertainty about the rates of sediment movement and the associated problem of developing margins of safety, as well as issues such as assessing sediment damage to intermittent and ephemeral streams. Implementation of TMDLs generally involves the adoption of Best Management Practices (BMPs) in areas within watersheds contributing to the water quality problem. Because it is impossible to directly monitor and enforce emissions of non-point source pollutants, approaches to TMDL development at the watershed level will include encouraging landowners to participate in the planning process and the voluntary adoption of BMPs. Public land managers can cooperate by incorporating sediment reduction goals into their management plans.

If landowners are to voluntarily adopt different management systems, at a minimum landowners will expect to understand and agree with the magnitude of the changes required to achieve water quality goals. Further, in some cases, landowners will expect to receive economic incentives. On rangelands, the key issue to understand for management purposes is how management affects vegetation and how vegetation on one hand contributes to the production of beef, and hence net income, while on the other hand protecting soil and holding water on the watershed to reduce peak flows that will move sediment. This paper presents a preliminary effort to calculate the cost of constraining sediment on rangelands through vegetation management.

Methods

While soil conservation has been an ongoing effort on many ranches, the social goal of reducing sediment leaving rangelands is equivalent to an additional constraint on ranchers. A constrained optimization model mimics a profit-maximizing rancher selecting management systems that are feasible, while also meeting a defined sediment reduction requirement.

Study area

The study area is the Walnut Gulch Experimental Watershed in southeastern Arizona. The watershed headwaters are in the Dragoon Mountains and the watershed drains westward toward the San Pedro River. A summary of previous research on the watershed can be found in Renard et al. (1993). The watershed is in the USDA Natural Resources Conservation Service's Major Land Resource Area (MLRA) 41, Southeastern Arizona Basin and Range. The watershed is primarily in the Land Resource Unit (LRU) 41-3, in the 12 to 16 inch precipitation zone, except for a small area in the upper end in the 16 to 20 inch precipitation zone. There are 15 ecological sites on the watershed.

MLRA 41 is a transition zone between the Chihuahuan and Sonoran deserts, with most of the precipitation coming from summer monsoons due to convective thunderstorms, while also receiving precipitation during the winter from frontal systems. Climate is semi-arid or steppe and soils are comprised primarily of gravelly sandy loams.

Although portions of five ranches are located within Walnut Gulch, no single ranch is completely contained inside the boundaries of the watershed. To maintain privacy, we are considering an artificial ranch, the "Walnut Gulch Ranch" with boundaries that coincide with the Walnut Gulch watershed boundaries. Most, but not all of the existing fences on the watershed were mapped. To simplify the analysis to consider only what a rancher might accomplish, the major paved roads, the airport, the city of Tombstone and a mine covering 2,800 acres or 8 percent of the watershed were eliminated from consideration. Figure 1 shows the excluded area along with the pasture boundaries and the three most dominant ecological sites.

Constrained optimization model

Workman (1986) lists previous applications of constrained optimization in range management that do not consider erosion or sediment issues. The preliminary model was designed to assess the effect of short-term reductions in stocking rates on biomass under average conditions. The basic factors in the model and their relationships are shown in Figure 2. We ignore some important elements in range management such as fluctuations in precipitation and medium-term biological effects, namely the improvement in ecological condition that is possible with management. In this MLRA, such improvement is primarily reflected in an increase of perennial midgrasses. This increase in grass production is highly desirable because it results in greater and more consistent forage production for the rancher and less erosion and decreased sediment yields.

The model does consider several major processes in ranch management: vegetation production, grazing, decay, and herd management, as well as erosion and sediment delivery. The heart of the model is the production of vegetation from the NRCS ecological site guides that is converted into canopy cover and the C factor of the Universal Soil Loss Equation (USLE) as described in Wischmeier and Smith (1978). Although the application of the USLE on rangelands is problematic (Spaeth et al. 2003), because it is easy to use and understand, and there is no accepted alternative, variations of the USLE are commonly used in models run on rangelands such as SWAT and SPUR and applications such as Rangemap (Guertin et al. 1998).

As the current form of the constrained optimization model is a linear programming model, linear approximations are used to represent curvilinear relationships. The optimization model currently uses a sediment delivery ratio of 0.41 (Lane et al. 2000) to estimate the sediment yield at the outlet independent of the where in the watershed the soil eroded, or how much vegetation is on the watershed.

Model parameterization

Rangeland ecological sites are a widely used concept in management to account for a site's potential to produce similar kinds, amounts and proportions of vegetation,

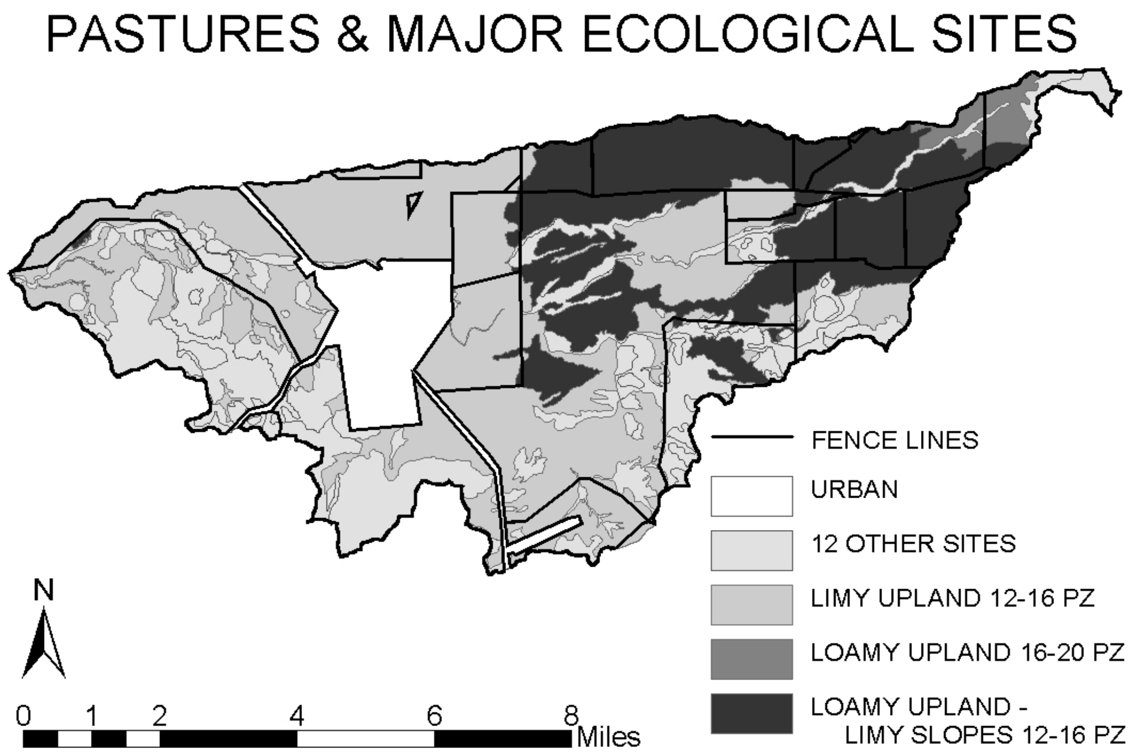

Figure 1. Walnut Gulch is a ranch consisting of pastures that are composed of various ecological sites.

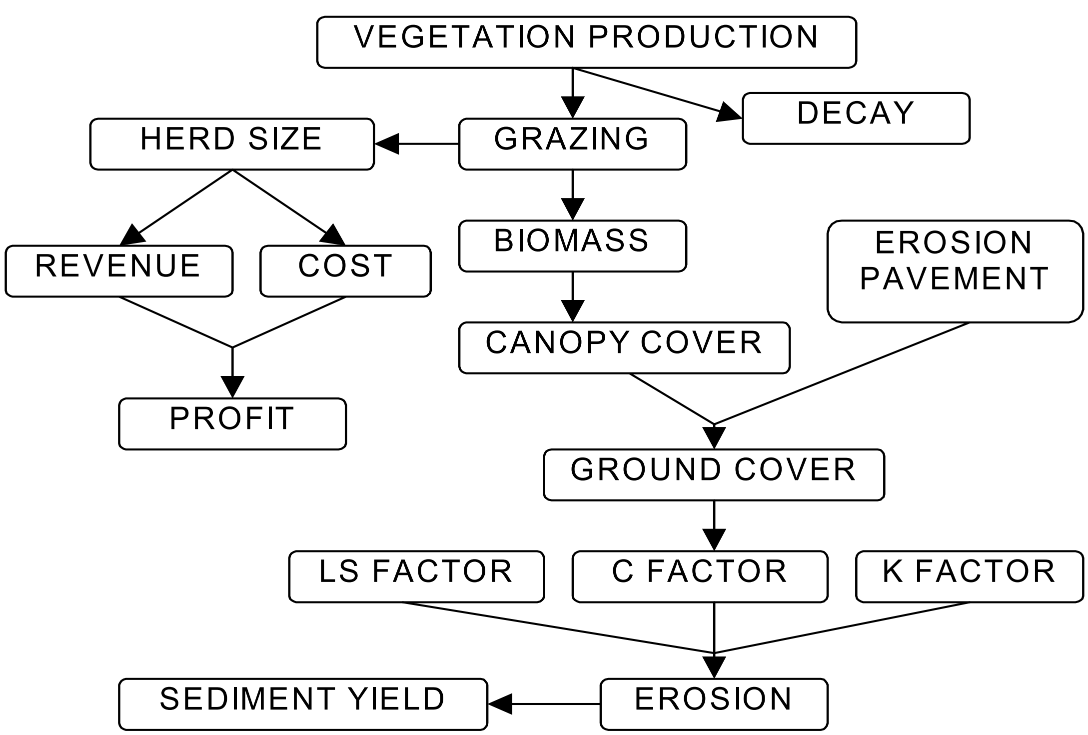

Figure 2. A number of factors contribute to the calculation of profit and sediment yield in the optimization model.

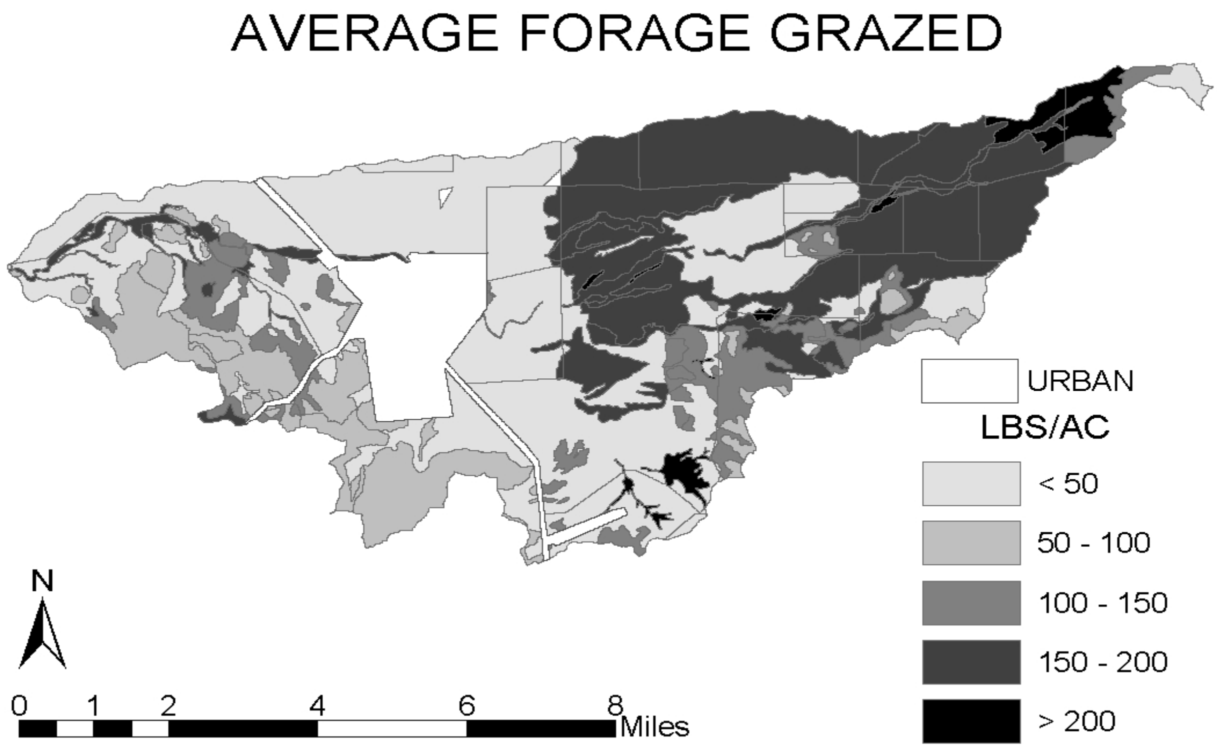

Figure 3. The optimization model distributes grazing according to forage availability.

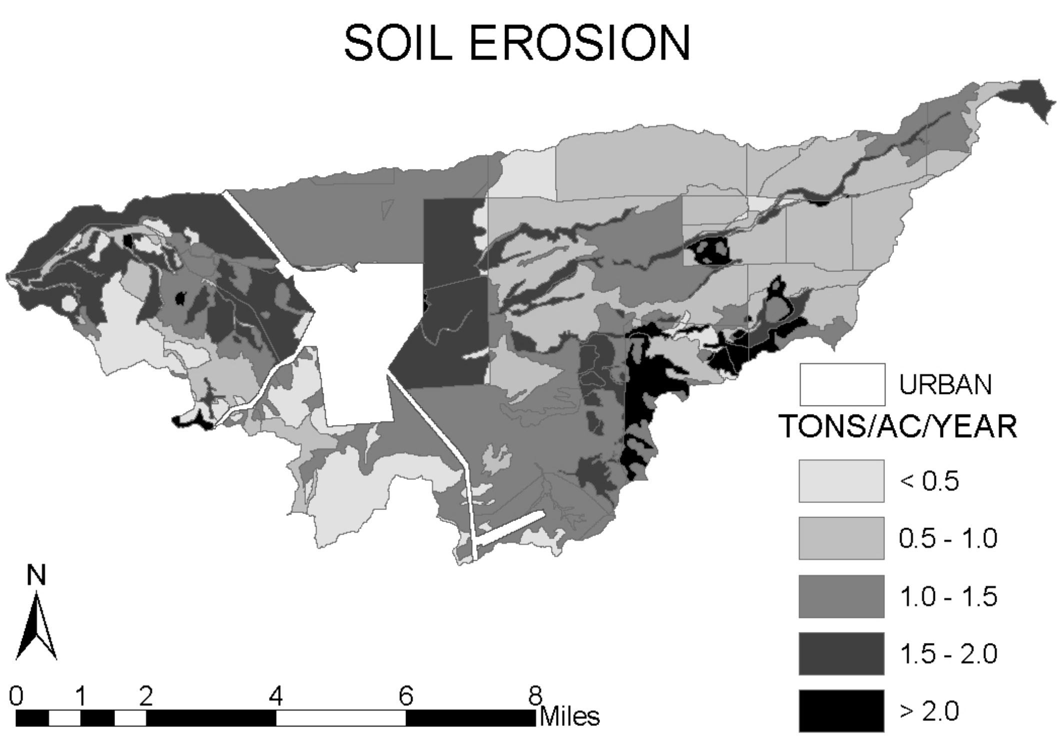

Figure 4. The USLE within the optimization model estimates soil detachment as affected by cover.

regardless of the current vegetation composition (NRCS 1997). The basic unit for this analysis is derived by overlaying pastures and ecological sites. All of the area within an ecological site in the same pasture is assumed to have uniform vegetation production and grazing intensity. The entire watershed is assumed to start in “fair” condition, which is by far the most common condition class in Arizona (Ruyle et al. 2000).

We assume the herd structure and size are adjusted while solving the model to limit grazing to a portion of the forage available. The model was solved with a utilization rate of 40% that is between the 35% used by the Forest Service and the older rule of thumb to “take half and leave half”. A portion of the heifers are kept and the remainder sold along with the steers and cull cows. Prices and budgeting relationships were taken from Teegerstrom and Tronstad’s (2000) Southeastern Arizona Region.

The USLE K*LS product was calculated using length and slope values from a 10 meter Digital Elevation Model of Walnut Gulch from the US Geological Survey as described in Hickey (2000). The rock fragment cover on the watershed was estimated using the slope-cover relationships developed for Walnut Gulch in Simanton and Toy (1994).

Model validation

The solution of the optimization model without a constraint on sediment should provide results that are similar to the current conditions on the watershed. The distribution of grazing according to the optimization model is shown in Figure 3. As one would expect, the Limy Upland sites did not support much grazing, while the sites to the east at higher elevations support more grazing, as do some bottomland areas to the south and west. As the production data used in the model come from the Ecological Site Descriptions, it is not surprising that there is a close match between the stocking rate from the model without sediment constraints and the safe initial stocking rates provided in the Ecological Site Descriptions, which are designed to be conservative. The area-weighted safe initial stocking rate for all 35,100 acres (55 sections) of the non urban portion of Walnut Gulch is a herd of 283 cows (approximately 5 head per section), whereas the model estimated a stocking rate of 326 cows (approximately 6 head per section).

The model estimates of the distribution of erosion across the watershed without enforcing a sediment constraint are shown in Figure 4. The estimate of erosion for the Limy Upland site is probably overestimated in part because of estimating the C factor with a linear relationship to cover which overestimates C at low values of cover. The estimate of 1.4 t/a for the Lucky Hills is well within the range of previous estimates at Lucky Hills. Simanton et al. (1980) reported actual erosion rates of 0.44, 1.78, and 0.61 t/a for subwatersheds at Lucky Hills for a 6-year period, although the two larger values are confounded by significant contributions from gully erosion. The overall average erosion rate calculated by the model on the rangeland portion of the watershed of 36,600 t/yr is about 1.1 t/a, which compares well with the 1.1 t/a reported for the whole watershed in Lane et al. (2000).

Because model erosion rates are similar to those reported in Lane et al. (2000), by applying their reported sediment delivery ratio of 0.41, the modeled sediment yield at the watershed’s outlet is comparable to their estimate for overall annual sediment yield. They report an estimated mean sediment yield of 16,700 t/yr. An earlier study for a shorter period (Lane et al. 1997) reported an annual sediment yield for the watershed of 26,500 t/yr. The model sediment yield without actions to reduce sediment of 15,000 tons is reasonable given the uncertainty in sediment yields, even though the model does not consider any soil erosion that would contribute to the sediment yield coming from the town of Tombstone.

Results

If Walnut Gulch were to be managed as a ranch, it would be economically stressed if the rancher did not have an outside source of income. Table 1 shows an estimated budget for the ranch, in fair condition, before any sediment control measures are implemented, with an estimated annual loss of roughly $4,500. The budget includes depreciation and wages, so such an enterprise could be cash flow positive while the assets of the ranch deteriorate.

Constraining the average amount of sediment from the watershed in the current model formulation could be misleading because there is no effect of increased cover on the energy available to move sediment out of the watershed. Nevertheless, near the current amount of cover the results should be reasonable, so as a first step to understanding the cost of reducing erosion by cutting herd numbers, the model was solved for progressively lower amounts of sediment.

Table 1. Budget without sediment control measures.

Income	Head	$/head	Sales $
Heifers	64	323	20,538
Steers	116	304	35,117
Cull Cows	65	374	24,327
Total income	326		79,983
Costs			
Variable cost	326	101	32,988
Fixed cost			51,561
Total costs			84,549
Profit (income – costs)			-$4,566

Figure 5 shows the increasing cost to the rancher of reducing erosion by running fewer cattle. Since without a sediment constraint the hypothetical Walnut Gulch rancher was losing money, even a small sediment constraint could put the rancher out of business. Even if all the cattle were removed in the short run, only 5,000 tons, or one seventh of the total estimated annual erosion, would be reduced. If the rancher were to sell the ranch, additional calculations would be needed to assess the impact of alternative land uses on erosion and sediment yield. A more promising option would be managing the ranch to the good condition class. The model solution for good condition with no sediment constraints is a herd of 428 cows, profit of $10,200 and a reduction of 5,600 t/yr in annual watershed erosion from the fair condition case without sediment constraints.

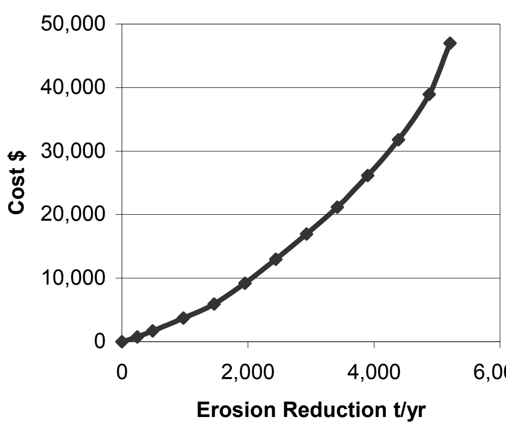

Figure 5. The cost to the rancher of reducing erosion.

In the current model formulation there is not much scope for reducing erosion simply by reducing the stocking rate. Even if the rancher could afford to reduce numbers, most of the soil protection comes from the rock cover (an average of 36% cover across the watershed), so management changes with moderate effects on vegetation will have limited effects on detachment, although there could be more significant effects on peak flows and channel processes. Evidence for this conclusion, at least for the portion of the watershed dominated by brush, can be seen in the fact that the Lucky Hills area has been fenced from grazing for more than 30 years, but still has not developed very much canopy cover (15% in May, 2003) and there are some signs of accelerated erosion.

Problems and future improvements

The study examined a simple constrained optimization model as a preliminary step in quantifying the cost of reducing sediment on rangelands. The list of improvements needed before this approach could be used with confidence is sobering in its length and complexity. From a management point of view, the scope of the management options should be widened to include facilitating practices such as additional fencing and water points to ensure a more even distribution of grazing. More important in the long-run would be the ability to alter the ecological composition of the plant community through management, although that would require a significant data collection effort and a dynamic optimization model. Installing stock ponds to act as sediment detention structures should also be an option in the model.

The second area needing significant research is the estimation of sediment yield as a function of management. A necessary first step would be the development of a historical sediment budget for Walnut Gulch. Changes to the sediment budget resulting from management could then be calculated using a distributed, continuous watershed model that would have to simulate the dominant channel processes and support the management practices mentioned above. The model would be calibrated using observed data from other locations and rainfall simulation experiments and simulation results would be used to define the relationships inside a revised optimization model. Issues such as urbanization and the uncertainty associated with precipitation should also be considered.

Conclusions

A method to estimate the cost of reducing erosion on a hypothetical ranch in southeastern Arizona was presented. On Walnut Gulch there appears to be little scope for significant reduction in erosion from reducing the stocking rate in the short term. This approach needs a number of improvements, nevertheless the approach provides a framework for assessing the cost to ranchers of reducing erosion, and ultimately sediment. The approach could provide better information on where changes are required, how large the changes need to be, and how much the changes will cost the rancher when developing TMDL plans on rangelands.

Acknowledgments

The authors appreciate the reviews of Leonard Lane and Dale Fox.

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