Optimization of Grazing Management for Watershed Sediment Control

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Abstract: Grazing on rangelands can increase erosion that is a major source of nonpoint source pollution. Grazing management is important in maintaining vegetation cover, which consequently impacts erosion and sediment yield. This paper uses a representative ranch model to define grazing management from an economic perspective. The model maximizes the profit of a representative ranch that can utilize all grazing lands in a watershed with constraints on forage resources, sustainable utilization, and production technology and sediment yield control objectives. A case study for the Walnut Gulch Watershed in Arizona showed a shift of the spatial distribution of optimal stocking rates with increasing sediment control objectives.

Keywords: Economics, Non-linear Programming, Rangeland, Spatial Optimization, Stock rate

1. INTRODUCTION

Rangeland forage provides diverse services to human beings. Many rangelands are facing the twin issues of maintaining the ranching economy and protecting the environment. With increasing environmental concern, the watershed services provided by rangeland vegetation are becoming more and more important. To maximize the social benefit, rangeland managers need to consider all the services that forage provide and find the best way to utilize forage.

Optimization techniques were used to find the best watershed sediment control from an economic perspective. Several studies have used the optimization techniques in watershed pollution control (Johnson et al., 1989; Prato et al, 1996; Srivastava et al., 2002; Khanna et al., 2003; Veith et al, 2003). These studies considered a representative farm economy of a watershed and find the solutions with the least cost for an environmental control objective. Heilman et al. (2003) used a linear programming model to study the best grazing management on a rangeland watershed. The highly nonlinear properties of range systems limited the applicability of LP on rangelands.

Increasing total maximum daily load (TMDL) plans demand better tools to understand watershed economics and environment. Under the Clean Water Act, states are required to identify water bodies that do not meet water quality standards and to develop TMDL plans for cleaning them up. A TMDL plan needs to identify all the pollution sources, define a safe load capacity, and allocate the capacities to different polluters to ensure the waters meet the environmental standards (USEPA, 1999).

This paper describes a representative ranch model to optimize the profits and meet the sediment control objective simultaneously. The model integrates biomass production, biomass conversion, ranch operation and erosion in the constraints. A case study was also made for the Walnut Gulch Watershed.

2. A REPRESENTATIVE RANCH MODEL

Grazing is a major land use in many rangeland watersheds. Improper grazing increases erosion and sediment yield, which can become major non-point source pollution problems and degrade the local water quality. For this type of watershed, the spatial distribution of the stocking rate can affect both ranch output and erosion. To aid such decision making for better management, we propose a model that maximizes the profit of all grazing outputs with constraints of forage resources, forage utilization as well as erosion and sediment yield.

We assume a representative ranch that can use all grazing lands in a watershed. Pastures are further divided along the ecological site boundaries, so that a land unit consists of an ecological site within a pasture. The biomass productivity in an ecological site is assumed to be homogeneous, as is grazing pressure. The objective of the ranch is to maximize its profits:

$$\text{Obj. Max } PRO = Revenue - Cost \quad (1)$$

Where PRO is the profit of ranch operation. The ranching objective is constrained by natural resources, animal behaviour, management and policy. The first group of constraints relates to biomass production. We considered that grass and brush are two major vegetation types on rangeland. Grass and brush production relationships are functions of the types and condition of an ecological site, and the local climate.

$$PG_{ij} = fg(BIO^*_i, EC_i, Climate, GP_i) \quad (2)$$

$$PB_{ij} = fb(BIO^*_i, EC_i, Climate, BP_i) \quad (3)$$

Where i is the index of ecological sites, j is the pasture index, PG_{ij} is the grass production, Bio^*_i is the climax production of ecological site i, ECi is the ecological condition, GP_{ij} is the grass percent in production, PB_{ij} is the brush production, BP_i is the brush percent in production, Climate is the type favourable, normal and unfavourable climate, and fg() and fb() are the grass and brush production functions respectively.

The second group of constraints requires that the forage utilization not exceed a sustainable level to keep grass vigorous for reproduction. For example, in the western USA, "take-half, leave-half" is a common rule of thumb.

$$UG_{ij} = GG_{ij} / PG_{ij} \quad (4)$$

$$UB_{ij} = GB_{ij} / PB_{ij} \quad (5)$$

$$UG_{ij} \leq UG^* \quad (6)$$

$$UB_{ij} \leq UB^* \quad (7)$$

Where UG_{ij} is the grass utilization, GGij is the grazed grass, UB_{ij} is the brush utilization, GB_{ij} is the grazed brush, UG^* is the maximum grass utilization, UB^* is the maximum brush grass utilization.

In a large and free roaming pasture, forage at remote and/or steep sites is less utilized. Spatial grazing behaviour is incorporated into the model by adding a discount factor for each land unit.

$$GG_{ij} \leq PGij * UG_{ij} * DF_{ij} \quad (8)$$

$$GBij \leq PBij * UB_{ij} * DF_{ij} \quad (9)$$

Where DF_{ij} are slope and distance discount factors. The values used in this study are derived from Holechek (1988).

Erosion of a land unit is estimated using RUSLE2.

$$ERO_{ij} = R\, K_{ij}\, LS_{ij}\, C_{ij}\, P_{ij} \quad (10)$$

Where ERO_{ij} is the erosion of one unit area, R, K, LS, C and P are the five RUSLE factors (Renard, 1997). The values of R, LS, K and P factor are assumed constant in the study period. The only factor affected by grazing is the C value. The C value can be derived using the equations from Weltz et al. (1987). The sediment delivery ratio (SDR) of upland erosion to watershed outlet is assumed constant in each land unit (Duan, 2005). The sediment yield at a watershed outlet is the sum of upland erosion multiplied by the SDR in the watershed. The sediment yield (SY) is constrained by the sediment yield objective.

$$SY = \Sigma_i \Sigma_j A_{ij} * ERO_{ij} * SDR_{ij} \quad (11)$$

$$SY \leq SYO \quad (12)$$

Where A_{ij} is the area of a land unit, SYO is the sediment control objective.

A typical cow-calf ranch is used as the ranch operation type. The number of cows is the stock number of ranch production scale and the number of calves, yearlings, bulls and culled cows are derived using standard ratios. Total forage to feed all livestock is computed based on Animal Unit Months (AUMs) of each livestock type and the number of animals per livestock type. The total forage grazed by livestock should not be less than the total forage requirement:

$$\Sigma_i \Sigma_j A_{ij} * (GG_{ij} + GB_{ij}) / W_{AUM} \geq \Sigma_k AUM_k * H_k \quad (13)$$

Where k is the index of livestock type, AUM_k is the AUM requirement per head and H_k is the number of one livestock type, W_{AUM} is the equivalent dry weight of vegetation needed per AUM.

The ranch revenue is the sum of ranch output sale of calves and culled cows. The costs include variable cost, such as feed cost, maintenance cost and fixed costs.

$$Revenue = \Sigma_k P_k * W_k * HS_k \quad (14)$$

$$Cost = VC(H_k) + FC \quad (15)$$

Where P_k is the livestock price of one unit weight, W_k is the average sale weight and HS_k is the sale number, VC is the variable cost that is the function of production scale, and FC is the fixed cost.

The optimization model will search for the largest production volume which meets all the above constraints. The model maximizes grazing to meet the profit objective, however the sediment objective will hold grazing in check, to maintain protective groundcover. There is a trade-off between these two objectives. The model can find a best solution that is not dominated by any other feasible solution. For each sediment control objective, SYO, there is a corresponding highest profit, PRO^*, forming a point on the production frontier.

$$PRO^* = H(SYO) \tag{16}$$

If we define the profit reduction from sediment control as the environmental cost, and assuming SYO_0 is the sediment yield without restriction, then the abatement cost curve can be derived by following equation:

$$C(\Delta SY) = H(SYO_0) - H(SYO_0 - \Delta SY) \tag{17}$$

where ΔSY is the sediment yield reduction, C(.) is the cost to achieve the sediment yield reduction, H() is the production frontier in equation 16.

3. CASE STUDY

3.1 Study Area

The Walnut Gulch Experimental Watershed (WGEW) is located in Southeast Arizona, USA. The watershed is a subwatershed of the Upper San Pedro River Basin (Fig. 1). The total watershed area is about 149 square kilometres. Brush and grass are the two major vegetation communities in the watershed, with grassland on the eastern area, brush on the western area near watershed outlet. Grazing land covers about 90% of the total watershed area.

3.2 Spatial Discretisation and Geo-processing

The whole watershed was discretised into land units by overlaying the ecological site layer (Fig. 1) and the pasture layer as if the ranch boundaries coincided with the watershed boundaries (Fig. 2). The parameters for each land unit were also computed using spatial analysis functions in Arc Info. The RUSLE K factor is computed from soil type and LS are computed from a DEM using the AML code from Hikey (2003). All Geo-processing was implemented in ESRI Arc Info.

3.3 Model Parameterization and Programming

The ecological site data are from Arizona Ecological Site Guides (NRCS) MLRA 41, Southeast Arizona. The ecological condition was set as fair for all pastures. The parameters of livestock operation and economics (price and cost) are from Teegerstrom and Tronstad (2000) for ranches in southeast Arizona.

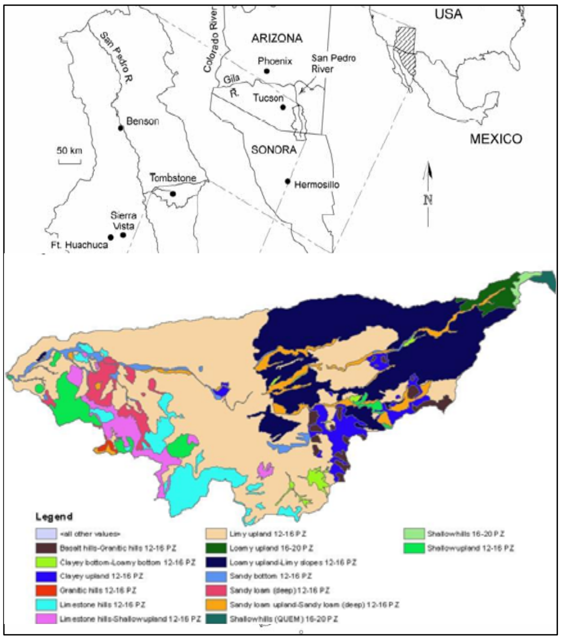

Figure 1. Location and Ecological Site of Walnut Gulch Watershed, adapted from SWRC (2003).

Figure 2. Pastures in Walnut Gulch Watershed

The optimization model was coded using the GAMS IDE and solved through the CONOPT solver (Brooke et al, 1998). After all parameters were written in a text file, the model was solved and results were stored in an output file.

3.4 Scenario

This case study addresses three sediment control objectives. The baseline assumes no sediment control, with forage grazed to maximize ranch profit. Then the sediment control objectives were set to reduce the sediment yield by 5, 10 and 15% of the baseline value.

4. RESULTS

The results include the optimal grazed grass and brush of each land unit, the corresponding erosion and sediment yield, the stocking rate and economic output of the ranch.

For the baseline scenario (current), forage grazing varied significantly on the landscape scale. The grasslands provide much more grazed forage per unit area than the brush lands. The erosion rate predicted by RUSLE2 varied with vegetation type, topography, etc. With an increasing sediment control objective, the overall grazing decreased. Grazing was first reduced in the areas near the watershed outlet at the sediment control level. Then the reduction spread gradually to the upstream areas with increasing sediment yield control objectives (Fig. 3).

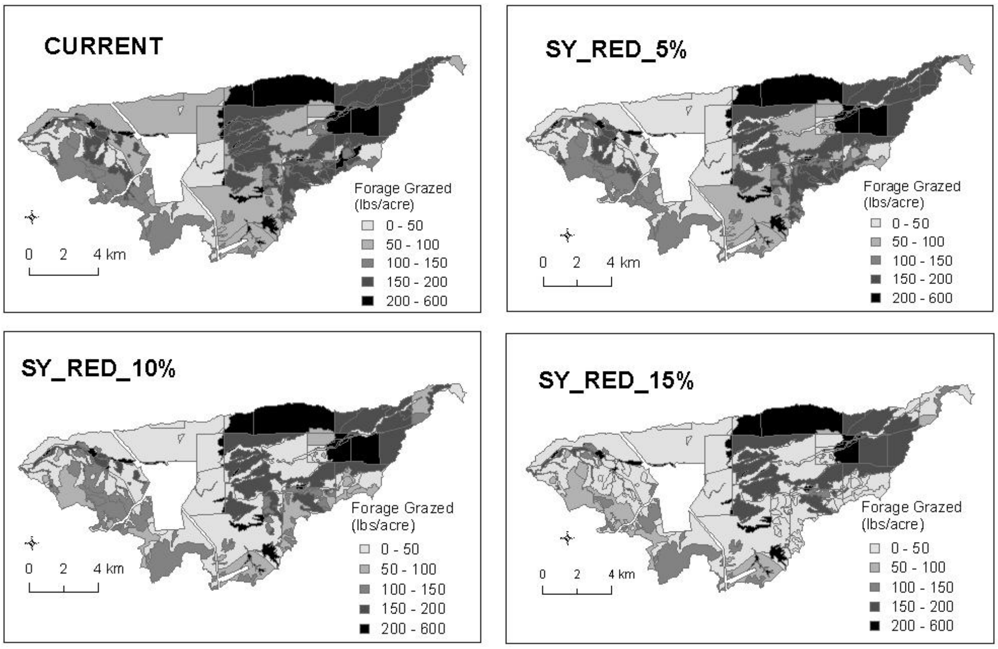

Figure 3. Amount of grazed herbage in the Walnut Gulch Watershed without sediment control (Current) and sediment yield reduction of 5%, 10% and 15% of Current.

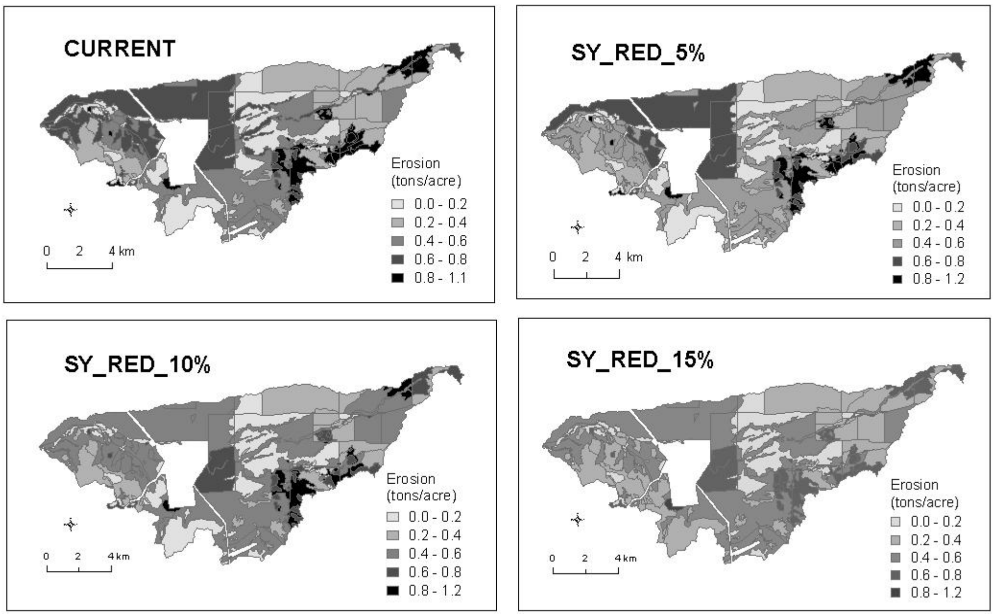

Figure 4. Upland erosion in the Walnut Gulch Watershed without sediment control (Current) and sediment yield reduction of 5%, 10% and 15% of Current.

The reduction of grazing at certain areas left more biomass on the ground, which reduced soil erosion. The erosion is reduced in the area where grazing is reduced (Fig. 4). Thus the erosion pattern showed a similar pattern with forage grazing pattern. The reduction of upland erosion consequently lowered the sediment yield at the watershed outlet.

The shifting pattern can be also shown by observing the stock rate changes in different pastures (Fig. 5). Stock rates are normalized with the maximum stock rate of pasture. Stock rates were first reduced in the pastures near watershed outlet, such as Pasture 11 and 18. Then grazing was reduced in Pastures a little further from outlet, such as Pasture 7 and 20 with more sediment reduction. The reduction occurred at the pasture even further from outlet, such as Pasture 22 21 14, 19. Grazing in the pastures far from the outlet such as 3 and 4, are barely affected by the sediment control.

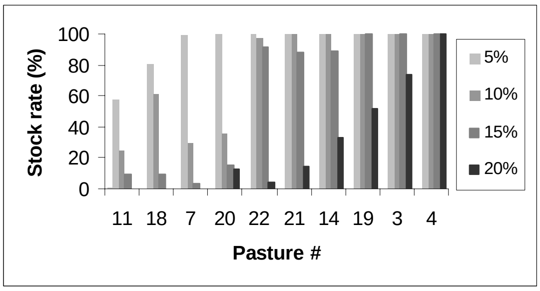

Figure 5. Stock rate change in different pastures in Walnut Gulch Watershed with sediment yield reduction of 5, 10, 15 and 20% of Current.

The abatement cost curve was derived according to Equation 17 (Fig. 6). The cost for small sediment yield reduction is low and increased much faster with higher sediment yield reductions. In other words, marginal cost of sediment yield reduction increases with greater sediment yield reductions.

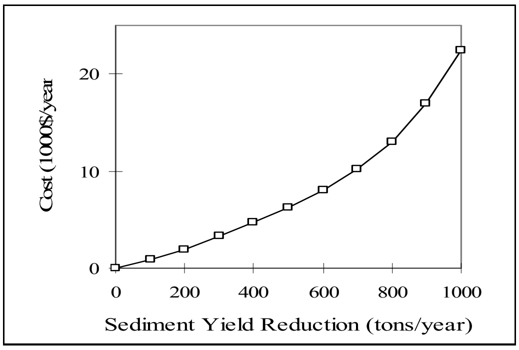

Figure 6. Abatement cost curve in Walnut Gulch Watershed.

5. DISCUSSION

The paper presents a nonlinear optimization model for a watershed management. The nonlinear functions can provide a better description of rangeland processes. However, one major issue with a nonlinear model is to check if a solution is locally or globally optimal. For this case study, we tested the same scenario with different initial input values and got the same solution. However, the general condition of a local optimum to be global optimum for this model has not been defined.

Grazing management is important in sustainable rangeland use. Traditional grazing management focuses on the development of a proper grazing strategy to maintain forage quality and vegetation productivity. Increasing environmental awareness requires that grazing management should also consider watershed services of vegetation, such as erosion control and water quality improvement. This model integrates all these aspects in a model and provides a new way for aiding in better grazing management.

The case study showed that grazing adjustment began from downstream areas and gradually shifted to the upstream areas with increasing sediment control objectives. This pattern was based on the special distributions of vegetation and topographic factors of the study. The pattern may change for other watersheds.

Because vegetation in the study watershed is generally sparse and forage utilization is restricted, the potential for erosion control by grazing manipulation is limited in a narrow range, for example about 20% of sediment yield for this case study. Even complete exclusion of grazing may not provide sufficient erosion reduction. Thus, grazing management provides a flexible but limited approach in watershed erosion control. In practice, there are many best management practices (BMPs) for rangeland sediment control. For example, stock ponds can detain sediment from a subwatershed, and riparian area revegetation could also reduce sediment transported into the stream. To develop water quality management plans, such as those required for Total Maximum Daily Loads (TMDLs) to meet water quality goals, planners need to select various practices that can reduce the sediment, even though there is great uncertainty associated with rangeland sediment budgets. Tools like the model proposed here provide a systematic way to understand the economic burden being put on the rancher by constraining sediment through grazing.

Parameterization of the model needs GIS analysis that many users are not familiar with. A spatial decision support system (Duan, 2005) was also developed to automate the analysis process. The model was integrated into the system. Users can perform the analysis through a web browser without GIS and optimization software and programming.

Unlike simulation models, the optimization model can give the optimal managements for defined objectives. Optimization can be important in watershed planning as the selection of the best practices could be challenging when lots of options are available. With improvement of rangeland modelling, the solution from optimization would be more reliable. In particular, improvements of vegetation and water erosion simulation are critical for better rangeland watershed management.

6. CONCLUSIONS

This paper presents a spatial optimization model to find the grazing pattern within a watershed to meet a sediment control objective. This model used a simple biomass production, spatial grazing, ranch operation and RUSLE model to aid in the understanding grazing, erosion and economics relationship on watershed level. The results of the case study show that grazing first was reduced near watershed outlet then the reduction shift toward upstream with more sediment control. Good grazing management can reduce sediment yield with less economic cost at the watershed level. The model can be useful in making trade-offs between grazing adjustments and other practices. However, the limitations in current vegetation and erosion prediction require further efforts in this area for better rangeland management.

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